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Monsanto Research Corp.
Dayton, OH

Prepared for

Industrial Environmental Research Lab.
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Vegetation		07D
Dust		07C
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PREFACE

The Industrial Environmental Research Laboratory (IERL) of the U.S. Environmental Protection Agency (EPA) has the responsibility for insuring that pollution control technology is available for stationary sources to meet the requirements of the Clean Air Act, the Federal Water Pollution Control Act, and solid waste legislation. If control technology is unavailable, inadequate, or uneconomical, then financial support is provided for the development of the needed control techniques for industrial and extractive process industries. Approaches considered include process modifications, feedstock modifications, add-on control devices, and complete process substitution. The scale of the control technology programs ranges from bench- to full-scale demonstration plants.

IERL has the responsibility for developing control technology for a large number of operations (more than 500) in the chemical and related industries. As in any technical program, the first step is to identify the unsolved problems. Each of the industries is to be xamined in detail to determine if there is sufficient potential environmental risk to justify the development of control technology by IERL.

Monsanto Research Corporation (MRC) has contracted wtih EPA to investigate the environmental impact of various industries that represent sources of pollutants in accordance with EPA's responsibility, as outlined above. Dr. Robert C. Binning serves as MRC Program Manager in this overall program, entitled "Source Assessment," which includes the investigation of sources in each of four categories: combustion, organic materials, inorganic materials, and open sources. Dr. Dale A. Denny of the Industrial Processes Division at Research Triangle Park serves as EPA Project Officer for this series. Reports prepared in this program are of two types: Source Assessment Documents and State-of-the-Art Reports.

Source Assessment Documents contain data on pollutants from specific industries. Such data are gathered from the literature, government agencies, and cooperating companies. Sampling and analyses are also performed by the contractor when the available information does not adequately characterize the source pollutants. These documents contain all of the information necessary for IERL to decide whether a need exists to develop additional control technology for specific industries.

State-of-the-Art Reports include data on pollutants from specific industries which are also gathered from the literature, government agencies, and cooperating companies. However, no extensive sampling is conducted by the contractor for such industries. Sources in this category are considered by EPA to be of insufficient priority to warrant complete assessment for control technology decision making. Therefore, results from such studies are published as State-of-the-Art Reports for potential utility by the government, industry, and others having specific needs and interests.

This study was undertaken to provide information on air emissions from prescribed burning. In this project, Dr. Ronald A. Venezia served as EPA Task Officer.

ABSTRACT

This report summarizes reported data on air emissions from prescribed burning, which is defined as the skillful application of fire in forest and range management under conditions that will confine the fire to a predetermined area and accomplish certain planned benefits.

Prescribed fire is used on a seasonal basis in all regions of the United States. The total vegetative material burned annually in prescribed fires (1978 survey) is estimated at 36.6 million metric tons, dry weight. Thirty-four percent of this total is burned in the Southern region, and the Pacific Northwest and Northern regions each burn 24 percent. Major fuel categories include piled or windrowed material (49%), naturally occurring understory vegetation and litter (31%), and broadcast (unpiled) material (20%).

Imperfect combustion in the natural environment of prescribed fires results in emission products from pyrolysis and oxidation similar to those expected from other carbonaceous fuels. Important among emissions are particulate matter, gaseous hydrocarbons, and carbon monoxide. Nitrogen found within the fuel and from the atmosphere enters the combustion product formation process to result in nitrogen oxides. Polycyclic organic matter and trace amounts of metal elements are also emitted. Production of sulfur dioxide is negligible. Amounts of emissions produced are highly varied due to variations in fuel moisture, arrangement, and species, as well as to differences in preferences for firing technique. By using smoothed emission factors derived for all fuels, estimates have been made of the total national emissions produced by prescribed fires each year. Estimated emissions from prescribed fires constitute 0.5%, 2.0%, and 2.7% of national emissions from all stationary sources of particulates, carbon monoxide, and hydrocarbons, respectively. Nitrogen oxides production was not estimated due to current uncertainties related to the fuel-bound, versus atmospheric, contributions for different fuels and fire types.

The emerging best-available control technology calls for quantitative appraisals of prescribed fire and its alternatives, and for specifying conditions that will limit air quality impacts in areas of concern. In those land management and air management communities where this technology is being developed, these

functions are defined as smoke management. Among the most viable of alternatives to burning is increased utilization of timber-harvesting residues, but even this alternative is limited by markets and energy costs. Other alternatives are also practised, but these, too, are energy demanding, costly, and, in some cases, will not take the place of fire as a natural component in ecosystem dynamics.

A net decrease of prescribed fire emissions concentrations in receptor areas is foreseen despite an expectation that more emmisions will be produced from this source during the next decade. The receptor area decrease is based most upon continued and foreseeable applications of smoke management technology. The emission production increase is based upon several actions which will offset use of alternatives to fire, such as restrictions on the use of herbicides and recent Presidential direction to increase timber supplied from federal lands.

This report was submitted under Contract No. 68-02-1874 by Monsanto Research Corporation under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from August 1975 to September 1979 and the work was completed as of September 1979.

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ABBREVIATIONS AND SYMBOLS

NFDRS	-- national fire danger rating system
POM	-- polycyclic organic material
PPOM	-- particulate polycyclic organic material
PSD	-- prevention of significant deterioration
S_X	-- standard deviation of the sample
$S_X/\bar{X}$	-- coefficient of variation
THC	-- total hydrocarbons
TLLMC	-- total litter layer moisture content
TSP	-- total suspended particulate matter
$\bar{X}$	-- arithmetic mean
$\bar{X}_\alpha$	-- quadratic mean
$\bar{X}_{L95}$	-- lower limit of the mean at the 95% confidence level
$\bar{X}_{U90}$	-- upper limit of the mean at the 90% confidence level
$\bar{X}_{U95}$	-- upper limit of the mean at the 95% confidence level
$\bar{X}_{U99}$	-- upper limit of the mean at the 99% confidence level

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SECTION 1

INTRODUCTION

Prescribed burning is the term applied by wildland managers in the United States to a form of open burning. The name is derived from the required prescription of atmospheric, fuel, and fire variables by which the burning is to be conducted under control to meet specified land management objectives. These objectives include fire hazard reduction, silviculture, disease control, range forage production, wildlife habitat improvement, and vegetation management for other purposes such as the protection and/or enhancement of rare and endangered plants and animals.

The objective of this report is to document the current state of knowledge of (1) the prescribed fire emissions source, (2) the geographic distribution of this source, (3) emissions produced, (4) control technology, and (5) outlook. To meet this objective, the Environmental Protection Agency and its contractor have been joined by the Forest Service, U.S. Department of Agriculture. The literature and specialists in the field have been heavily drawn upon in its preparation.

As a state-of-the-art study covering a wide diversity of practice and an extremely variable set of natural elements, no attempt is made to arrive at a direct assessment of effect upon air quality. Rather, regional emissions production estimates are made using the limited emissions data available. Then, by examining how concentrations of these emissions may be locally predicted for individual fires under prescribed conditions, a view of the effect in receptor areas has been afforded.

A similar open burning operation, namely, agricultural open burning, which includes the burning of residues of field crops, row crops, and fruit and nut crops for field sanitation, residue removal, and residue disposal, is not covered in this report.

SECTION 2

SUMMARY

The name "Prescribed Fire" implies more than open burning. Prescription criteria are established by which fires are confined to areas under treatment, and are employed as a means of meeting specified land-management objectives, in all regions of the United States. Even when only one objective is specified, multiple benefits will usually accrue to the land. For example, when fire is prescribed to reduce residues from timber harvesting, introduction of this natural ecological element will tend to promote improved wildlife habitat. Thus, while used only intermittently on the same tract of land, prescribed fire is regarded by land managers to be an ecologically sound practice for preventing and/or reducing intensity of wildfires, for maintaining site productivity, and for meeting many other land management objectives.

The total vegetative material burned annually in prescribed fires (1978 survey) is estimated at 36.6 million metric tons,[a] dry weight. Thirty-four percent of this total is burned in the Southern region, and the Pacific Northwest and Northern regions each burn 24 percent. Major fuel categories include piled or windrowed material (49%), naturally occurring understory vegetation and litter (31%), and broadcast (unpiled) material (20%). Unlike agricultural open burning, which has been covered in a separate report, the fuels consumed in wildland prescribed fires are very heterogeneous.

Imperfect combustion in the natural environment of these fires results in emission products from pyrolysis and oxidation which may include several thousand compounds similar to those expected from other carbonaceous fuels. Important among emissions are particulate matter, gaseous hydrocarbons, and carbon monoxide. Nitrogen found within the fuel and from the atmosphere enters the combustion product formation process to result in nitrogen oxides. Polycyclic organic matter and trace amounts of metal elements are also emitted. Production of sulfur dioxide is negligible.

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[a] 1 metric ton equals 10^6 grams; conversion factors and metric system prefixes are presented at the end of this report.

Amounts of emissions produced are highly varied due to variations in fuel moisture, arrangement, and species, as well as to differences in preferences for firing technique. This variability is reflected in overall emission factor ranges such as 2.5 g/kg to 79 g/kg for total suspended particulate matter, where grams emitted are per kilograms of fuel actually consumed, dry weight. By using smoothed emission factors derived for all fuels, estimates have been made of the national prescribed fire total emissions production each year for pollutants covered by the National Ambient Air Quality Standards. These production estimates are included in the data which follows. Also shown are estimates of the relative national contribution of the estimated annual average prescribed fir production to the total produced by all sources,[a] expressed as percentages.

Criteria pollutant	Thousands of metric tons produced			Percents at average value
	Lower limit	Average	Upper limit	
Total suspended particulate matter	366	622	878	0.5
Carbon monoxide	1,464	2,049	2,634	2.0
Total hydrocarbons	183	329	476	2.7
Nitrogen oxides	Not estimated			
Sulfur dioxide	Negligible			

Nitrogen oxides production was not estimated due to current uncertainties related to the fuel-bound, versus atmospheric, contributions for different fuels and fire types.

Several studies have shown that a high percentage of the mass of total suspended particulate matter emitted from prescribed fires is in the submicron size range. On a number basis, the average aerodynamic particle diameter has been shown to be about 0.1 μm.

The emerging best-available control technology calls for quantitative appraisals of prescribed fire and its alternatives, and for specifying conditions that will limit air quality impacts in areas of concern. In those land management and air management communities where this technology is being developed, these functions are defined as smoke management.

Among the most viable of alternatives to burning is increased utilization of timber-harvesting residues, but even this alternative is limited by markets and energy costs. Other alternatives

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[a]Including fugitive dust. See Section 5 for further definition of sources.

are also practiced, but these, too, are energy demanding, costly, and in some cases, will not take the place of a fire as a natural component in ecosystem dynamics.

Smoke management appraisals of prescribed fire are to include an assessment of predicted downwind emissions concentrations for specified fuels, fire, and atmospheric variables. A smoke management operating plan is drawn up using those specified variables found in the appraisal to maintain acceptable receptor area concentrations. The major control features of these operating plans are those which limit amounts of fuel to be burned, the selection of a best-firing technique, and meteorological scheduling. Each of these control measures can be further specified in individual fire prescriptions. Some operating plans need only be fairly simple, while others must be sophisticated. In several areas where large amounts of fuel are burned each year, and where maintenance of air quality is a challenge, forms of centralized smoke management have been effected. There, the amount of burning to be scheduled each day will vary, depending upon a prediction of the downwind consequences of all proposed burns, individually and in combination. The more advanced smoke management technology being brought on line now utilizes automated data processing of near-real-time observed and forecast weather variables in operational adaptations of EPA-recommended dispersion models.

A net decrease of prescribed fire emissions concentrations in receptor areas is foreseen despite an expectation that more emissions will be produced from this source during the next decade. The receptor area decrease is based most upon continued and foreseeable applications of smoke management technology. The emission production increase is based upon several actions which will offset use of alternatives to fire, such as restrictions on the use of herbicides and recent Presidential direction to increase timber supplied from federal lands. Much of this latter action will occur in defective oldgrowth (i.e., virgin) stands. Additional actions bearing upon the outlook for an upward trend in emissions production are those taken to meet the need to conserve energy and to reduce economic demands; lessening of the fuel and dollar expenses for wildfire suppression by trading off prescribed fire and wildfire emissions is an important example.

Areas of major importance to further characterization of the prescribed fire source are: (1) development of improved and interim emission and heat-release factors; (2) completion of mathematical models of the fuel and fire interactions affecting emission rate and heat-release rate; (3) quantification of emissions of "non-criteria pollutants", (4) continued systematization of the available and emerging control technology in an appropriate smoke management format. Improved and additional interim emission and heat-release factors are needed for a wide variety of fuels and burning situations. These need to be developed as best-available

estimates even though parallel work is in progress which it is hoped will obviate their need in time. The longer-term parallel work will complete models of fuel and fire interactions and is targeted at solving the problem of natural variability which now confronts experimenters attempting to derive factors from in situ prescribed fires. As with other sources of emissions, prescribed fire smoke contains important constituents for which National Ambient Air Quality Standards have not been set; quantification of these "non-criteria pollutants" should continue to be incorporated in current research in anticipation of future standards. Even though control technology in the form of smoke management is now mainly in an emerging status, it is sufficiently advanced to call for emphasis upon systems by which land managers and air quality personnel may bring about needed applications.

SECTION 3

SOURCE DESCRIPTION

GENERAL CHARACTER

Source Definition

Prescribed burning is the skillful application and confinement of fire in forest and range management under specified conditions of weather, fuel moisture, and soil moisture that will accomplish planned benefits such as fire hazard reduction, control of understory species, seedbed and site preparation, grazing enhancement, wildlife habitat improvement, and forest tree disease control. It differs from wildfire in that it is employed only under controlled conditions and is managed so that beneficial effects outweigh costs and detrimental effects.

Unlike most sources of emissions, prescribed fires are mostly seasonal and, as individual fires, are transient. While a large landowner may have an annual program of prescription burning, the individual fires each year will usually be limited to those days within a few months when prescription criteria are met. Fires located within the same ownership are scheduled either following timber harvesting, or on cycles ranging from every two to every eight years, depending upon rates of natural vegetation regrowth and litter accumulation.

Prescribed burning is a portion of the overall open burning segment of combustion sources of air pollution in the United States. A similar open burning operation, namely, agricultural open burning, is covered in a separate report (1), and is not included in this study. Agricultural open burning covered in that report includes burning of residues of field crops, row crops, and fruit and nut crops for purposes of field sanitation, residue removal, and residue disposal.

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(1) Chi, C. T., and D. L. Zanders. Source Assessment: Agricultural Open Burning, State of the Art. EPA-600/2-77-107a, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, July 1977. 74 pp.

Fire As A Natural Agent

Fire in the past was a major natural environmental factor in controlling plant succession, species composition, and age structure in forests (2, 3). In the wilderness state, fire tended to follow natural fuel accumulations, with great conflagrations in drought periods leading to the creation of extensive open grass and brush areas. In the long intervals that followed, grass and brush would gradually be replaced by the prevalent forest types through the process of natural succession. Succession is defined as the more or less orderly pattern of events and processes in nature whereby plant and animal species replace each other as a result of changing environment over time.

Some plant types are dependent upon fire for the maintenance of their position in the ecosystem. Aspen and jack pine in the Lake States, longleaf pine in the South, ponderosa pine in the Southwest, and lodgepole pine in the Rocky Mountains are just a few of the species whose natural regeneration and survival are related to periodic fires. With the absence of natural disturbances like fire, species such as pines tend to be succeeded by more shade-tolerant species such as true firs and hardwoods. Disturbances which man regards as "natural disasters" are frequently localized and classed as relatively minor ecological factors overall. Research during the last 40 years has shown that fire is neither minor nor abnormal, but, rather, a major factor for most of the terrestrial habitats of the world. Man's failure to recognize ecosystem adaptations to fire has indeed been cited as the source of a great deal of mismanagement of our natural resources (4).

Many trees and other native plant and animal species in areas of naturally high fire frequency are adapted to fire through the process of natural selection. Adaptations to fire found in indigenous species include: serotinous cones of lodgepole pine in the West, and of sand pine in the East, for both of which the heat of fire induces release of seeds; light, wind-disseminated seed of some species such as aspen, cottonwood, and western larch

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(2) Fire in the Northern Environment - A Symposium. C. W. Slaughter, R. J. Barney, and G. M. Hansen, editors. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, 1971. 275 pp.

(3) Prescribed Burning Symposium Proceedings. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, 1971. 160 pp.

(4) Odum, E. P. Fudamentals of Ecology, 3rd Edition. W. B. Saunders Co., Philadelphia, Pennsylvania, 1971. 574 pp.

that can blow from great distances, and fire-resistant bark of ponderosa pine, longleaf pine, red pine, Douglas-fir, and redwood. Chaparral is regarded as a fire-adapted plant community in which recycling of the plant succession takes place each time enough fuel accumulates and is ignited.

Use of Fire in Forest Management

Reduction of Hazardous Fuels--

A principal use of prescribed burning is that of hazard reduction - a means of reducing fuel accumulations to levels which will seldom support high-intensity wildfires. Fuel buildups composed of vegetative growth and litter accumulations are an inherent part of the forest environment, and they require some measure of control if eventual damage from wildfires is to be minimized. In pine stands of the Coastal Plains and Piedmont areas of the South, for example, heavy accumulations posing a serious threat from wildfire may develop within 4 to 5 years (5, 6).

Prescribed burning is also used to remove residue and nonmerchantable species remaining after a harvest cut of timber. In three Pacific Coast states (California, Oregon, and Washington), the annual logging residue (i.e., slash) has been estimated at 11×10^6 metric tons on a bone-dry basis (7). The removal of these fuel concentrations is desirable because unburned slash has been a primary fire control problem in the Pacific Northwest since the late 1940's (8).

Fire exclusions in forested regions results in a gradual accumulation of fuels - leading to the potential for a conflagration if a wildfire does escape during extremely dry conditions. Property loss, loss of life or injury, mortality of merchantable timber, and other resource losses are examples of directly measurable, or tangible, losses from such large, high-intensity fires, even though prompt salvage of timber may reduce the overall net loss.

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(5) Mobley, H. E., R. S. Jackson, W. E. Balmer, W. E. Ruziska, and W. A. Hough. A Guide for Prescribed Fire in Southern Forests. U.S. Department of Agriculture, Forest Service, Atlanta, Georgia, May 1977. 40 pp.

(6) Davis, L. S. and R. W. Cooper. How Prescribed Burning Affects Wildfire Occurrence. Journal of Forestry, 61(12): 915-917, 1963.

(7) Grantham, J. B. Forest Residue: A Forgotten Source of Energy. Paper Processing, 10(2):17-20, 1974.

(8) Cramer, O. P. Disposal of Logging Residues Without Damage to Air Quality. Technical Memorandum WBTM WR-37, U.S. Department of Commerce, Salt Lake City, Utah, March 1969. 8 pp.

An intense wildfire may consume the entire litter mat and expose the mineral soil to erosion forces. In contrast, prescribed burning is employed only under controlled conditions, when temperature, wind, and fuel moisture meet prescribed criteria for accomplishing land management objectives without damage to crop trees and soil. In a proper prescribed fire, the soil is seldom bared except possibly in the small areas adjacent to piled debris, or to long-burning heavy fuels, where the surface litter will become dried out and burn. This is illustrated by the estimated litter fuel available to burn in southern prescribed fires. When published tables are used in reverse, an indicated range of from about 35 percent to about 98 percent is left unburned when the total litter layer moisture content (TLLMC) varies from 10 percent to 200 percent, respectively (9).

Site Preparation--
Prescribed burning is employed in preparing a proper site for tree seeding or planting. Fire aids in the removal of litter and debris which obstructs seed gemination; reduces upper organic layers, thereby exposing adequate mineral soil for new seedlings; and reduces competition for moisture, nutrients, heat, and light by temporarily reducing or eliminating competing vegetation such as shrubs, herbs, and grasses, as well as mosses and lichens. It may also release quantities of essential mineral elements needed for plant growth. These elements are present in the ash layer, and represent a recycling of nutrients accumulated in the litter, humus, wood, bark, and foilage of the old forest. Production of some commercially important species of timber calls for clear areas in which the seedlings can receive full light; hence clear-cutting in small blocks has become a common practice in timber management. Clearcutting deposits large amounts of residue on the cut areas--cull logs, limbs, tops, foilage, and brush. Burning is used to remove the logging residue (i.e., slash) and kill brush that would compete with the young trees of the next crop.

Control of Undesirable Species--
The pure pine stands of the South are a subclimax forest maintained largely by fires. In the absence of fire, most southern pine sites succeed to a climax type of hardwood. If these species are permitted to invade and develop, regeneration of pine is very difficult.

In many grasslands, the gradual colonization by woody species is retarded or reversed by fire because the brush stems are scorched by fire, resulting in "dieback" even if new sprouts do gradually reappear. Not all brush species resprout following scorching of root crowns.

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(9) Southern Forest Fire Laboratory Personnel. Southern Forestry Smoke Management Guidebook. Forest Service General Technical Report SE-10, U.S. Department of Agriculture, Asheville, North Carolina, and Macon, Georgia, 1976. 140 pp.

Wildlife Habitat Improvement--
Prescribed fire is used in wildland management for improving food and cover conditions for certain threatened and endangered species as well as the more common wildlife species. Quali, grouse, deer, pheasant, turkeys, and other animals are supported best by varied vegetative patterns which include open areas, and areas where the early successional stages of the forest are found. As the forest matures, open areas and the young trees, shrubs, and herbs upon which animals depend disappear. Fire removes unpalatable brush and litter, stimulates new shrub and sprout growth, and increases yield and quality of herbage, legumes, and browse from hardwood sprouts. Seeds and insects are also more plentiful on burned areas.

Range Improvement--
Large areas of land in the United States support weed, brush, woodland, or forest types where forage production can be greatly increased by conversion to grassland or some other more desirable forage cover. Prescribed fire is used in the conversion and regeneration of these areas to improve the range for grazing. For example, in mesquite-tobosa communities in west Texas, fire is used to remove accumulated litter, increase yields and palatability of tobosa, reduce mesquite canopy to acceptable levels, top-kill misquite, kill mesquite, kill 40 percent to 80 percent of three species of cactus, and kill undesirable broomweeds (10). Where cattle are raised on forested ranges, fire is used to improve forage production without affecting the pine overstory. Wire-grasses and principal herbaceous plants of the pine wiregrass type green up after burning. Periodic, low-intensity fires control competition and maintain the grass species. In the absence of fire, total herbaceous cover declines after 6 to 8 years, and the range becomes less desirable for animal use (5).

Disease Control--
Prescribed fire has a role in the control of forest tree diseases. For years, fire has been recognized as the most practical means of controlling brown spot disease (*Scirrhia acicola*) of long-leaf pine seedlings. Brown spot is a fungal infection that defoliates and weakens young plants, prevents height growth, and eventually kills. As an example of the critical nature of some fire prescriptions, temperatures in brown spot burning should be hot enough to consume or scorch all infected needles, but should not kill the terminal bud. Burning the infected needles reduces the number of spores available to infect the seedlings the following spring.

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(10) Wright, H. A. Range Burning. Journal of Range Management, 27(1):5-11, 1974.

Insect Control--
The use of prescribed fire to control the red cone pine beetle has been documented (11) as have other agriculture and forestry applications, including both habitat changes and direct (heat) dosages (12).

Access, Visibility, and Esthetics--
Both for public enjoyment and timber management operations, fire is prescribed to improve access by reducing dense understory vegetation. Diversity of cover also results from the mosaic of different age classes that will be found in large tracts of land treated in this way. Vegetative diversity further supports a variety of birds and animals, and also provides greater opportunities for them to be seen in the park-like stands adjoining age-classes of vegetation that are their optimum habitat (13).

Timing

A critical factor affecting characterization of prescribed burning is timing. Prescribed fires are of comparatively short duration and are mostly seasonal in nature. Individual fires may last from a few hours to a day, except for larger pieces of wood, which may sometimes smolder for weeks. The same tract of land is then left unburned for a period of from one to ten years or even longer. Annual or biannual burns may take place in areas subject to wildlife habitat improvement, such as grasslands used for quail cover. Understory burning in pine forests generally takes place every five years, but may be longer in areas where growth is slow.

In the prescribed burning of chapparal in the West, timing is very important. Up to approximately seven years after the last burn, litter is lacking and the new growth will not carry fire alone. By about the tenth year, however, dead stems and twigs accumulate and, in combination with the seasonally-dried living vegetation, will burn explosively if set afire.

Prescribed fire used to dispose of timber-harvesting residues may take place as infrequently as once every 25 to 100 years, depending on the cutting cycle.

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(11) Miller, W. E. Use of Prescribed Burning in Seed Production Areas to Control Red Pine Cone Beetle. Environmental Entomology, 7:698-702, 1978.

(12) Miller, W. E. Fire as an Insect Management Tool. Bulletin of the Entomology Society of America, 25:137-140, 1979.

(13) Mobley, H. E. Personal communication. U.S. Department of Agriculture, Forest Service, Macon, Georgia, July 1979.

The season of the year is also important in prescribed burning. Both the moisture content of the fuel and the ambient temperature must be within given limits for a good burn, and those parameters vary on a seasonal basis. For example, late winter or early spring are generally the best seasons for prescribed understory fires in southern pine stands, but when the timber is clearcut in the South, the burning may be done whenever fuel and weather conditions permit.

Constraints on Burning

Smoke management is being increasingly applied to prescribed fires. This response to the need to maintain air quality can itself be an important constraint on burning. A review of the checklists and smoke management procedures reveals that the number of days available for burning may become more limited as a result (9). If burning is scheduled with fewer years between prescribed fires in the same area, less fuel will accumulate, and, thus, less emissions will be produced per unit area per burning year. But, this too must be classed as a constraint on burning if the result is to force other land-management compromises and/or additional expenditures.

Other prescribed burning constraints are found in a differentiation of the two broad categories of burning, (1) where a tree overstory exists, and (2) where no tree overstory exists. The success of the first type is dependent on conditions such as steady winds, cooler temperatures, and proper burning techniques that minimize damage to the crop trees. The main considerations in the second case are optimum removal of debris or unwanted vegetation from an area, while keeping fires confined to areas being treated. Different techniques are used for each situation.

When burning under a tree overstory, a forest manager must wait for those days when temperatures are relatively low and when winds are likely to remain steady for the burning period. He can then ignite the downwind side of his area and allow the fire to back slowly against the wind. If fuel loading is light, and the overstory trees are old enough, a higher intensity heading fire may be acceptable.

When burning areas free of an overstory, there is obviously no need for concern about damage to an overstory. Precautions to prevent fire escape, to minimize air pollution downwind, to avoid soil damage and unwanted runoff of ash, etc., need to be considered. Because flames of high-intensity heading fires will lean further, these are often used when fuel continuity is poor.

FUELS

Surface Fuels

Surface fuels include all combustible material lying on or immediately above the ground, as shown in Figure 1 (14). Because roots or the lower layers of duff, and highly organic soils, will on occasion also burn with these more obvious fuels, they are sometimes also included in the surface fuel category, or may be known as "ground fuels." In this report all such fuels are classified as "surface fuels." The principal fuel materials are duff, surface litter, and low-lying vegetative growth.

Duff--

Duff is composed of matted layers of partially decomposed organic matter and highly organic soils such as humus, peat, or muck on the forest floor. Duff is normally moist and rather tightly compressed and has little influence on the forward rate of spread of a fire, supporting instead a slow, smoldering type of combustion. A path for the fire to creep between patches of more flammable material may, however, be found through duff. Normally, only the uppermost layer of duff is consumed in the course of a fire. During periods of drought, however, a severe wildfire may consume all of the organic duff layers, exposing the mineral soil to erosive forces.

Surface Litter--

Litter on the forest floor normally consists of fallen leaves or needles, twigs, bark, cones, and small branches that have not decayed sufficiently to lose their identity. It also includes logs, stumps, and large limbs. Dry, dead leaves and needles are highly flammable. Flammability depends on the physical characteristics of the fuel element and on its arrangement. A litter bed of ponderosa pine needles, for example, is more flammable than one of spruce or Douglas-fir needles. Pine needles are much larger in size and are shed in clusters of two-to-five needles to form a loose, well-aerated mat. In contrast, spruce or Douglas-fir needles are shed singly, are smaller in size, and form a more compact moisture-retaining mat which ignites and burns more slowly. Leaves or needles attached to fallen branches are particularly flammable because they are fully exposed to the air and dry easily. Fine branches, small limbs, bark, and other similar materials are important to influencing rate of spread and general fire behavior. Fine dead wood in a dry condition ignites easily and may act as kindling material for larger, heavier fuels. In areas where there is a great accumulation of fine dead wood, an extremely hot fire can develop. Large amounts of fine dead wood accumulate on the ground in fire-killed, diseased, insect-damaged

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(14) Intermediate Fire Behavior. U.S. Department of Agriculture, Forest Service, August 1972. 59 pp.

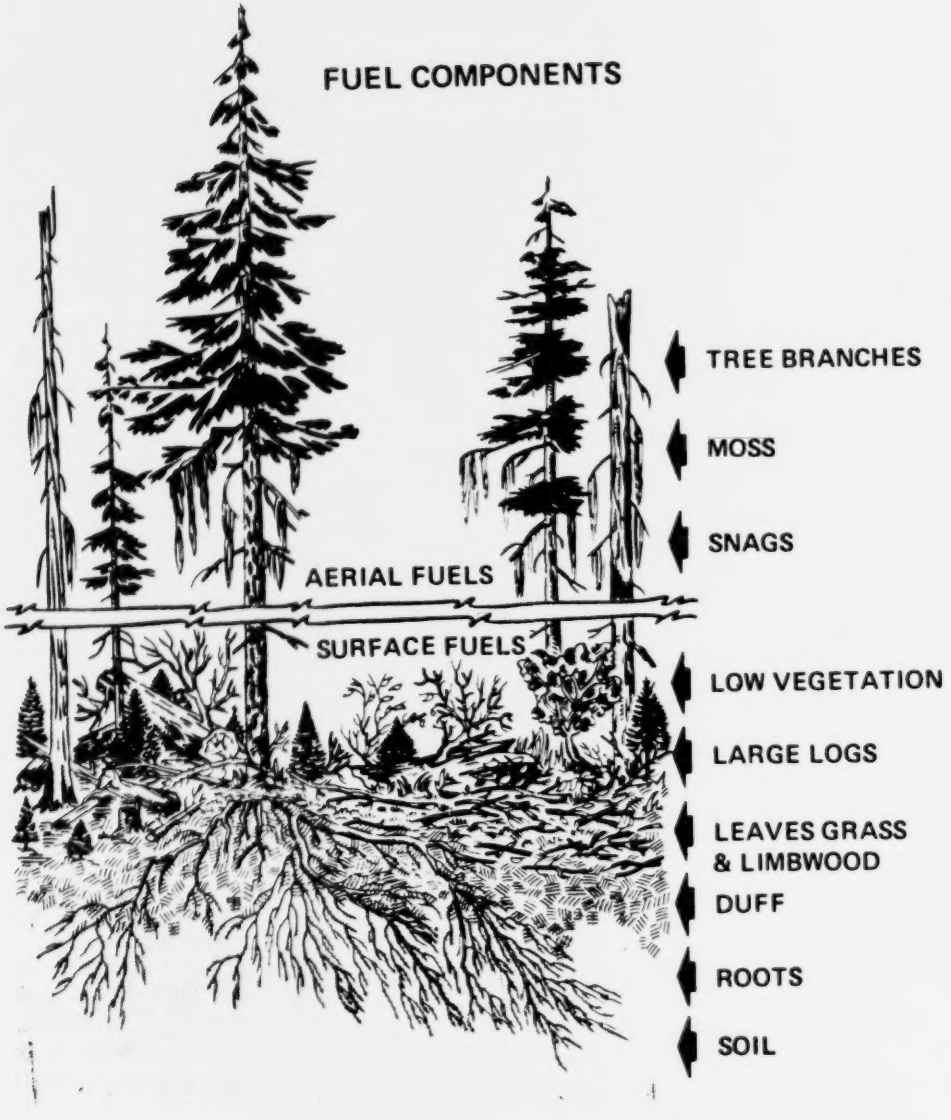

Figure 1. Principal components of surface fuels and aerial fuels (14).

or killed, wind-damaged, and ice-damaged timber stands, or in areas containing logging slash. Under dry conditions, such areas will burn violently with intense heat.

Heavy fuels, such as logs, stumps, and large limbs, require long periods of hot, dry weather before they can become very flammable. Usually this material is only partially consumed in short-lived and less intense broadcast fires (i.e., fires which burn on a broad front within a delineated area). Piling techniques are commonly used in management programs to effect more complete consumption. Extremely hot fires may develop in piles of logs and large limbs because the various fuel components radiate heat to each other.

Low-lying Vegetative Growth--
Surface growth includes grasses, low shrubs, ferns, seedlings, and other small herbaceous plants. Flammability depends to a large extent on species, moisture content, weather, and seasonal variations. During the growing season, green and succulent new growth can retard fire spread. However, when dry, the entire plant will contribute to support of fast moving surface fires. Open grass and brush types are an important fuel because of their usual continuity and their complete exposure to the drying effects of the sun and wind.

Aerial Fuels

Aerial fuels include all live and dead material located in the upper forest canopy. The main aerial fuels are tree branches and foilage, snags, high brush, mosses, lichens, and epiphytic plants. Flammability of tree branches and foilage is dependent on type, moisture content, and phenology of growth - volatile oils and resins contained in pine needles make tree branches and crowns of coniferous trees an important component in aerial fuels. Live leaves of hardwood high-forest tree species will not normally carry fire, but those of chaparral and related species do at times when fuel moisture is low.

Dead branches and bark on trees and snags (dead standing trees) are an important aerial fuel. Concentrations of dead branches and foilage, such as found in insect- or disease-killed stands, can even carry fire from tree to tree. Various species of moss, lichens, and epiphytic plants hanging on trees are light and flashy aerial fuels. These fuel elements react quickly to changes in relative humidity and provide a means of spreading fires from ground fuels to other aerial fuels, or from one aerial component to another.

FIRE BEHAVIOR

Fuel Properties

Materials consumed in prescribed fires consist of tree parts, understory vegetation, ground litter, shrubs, and grasses. Elemental analyses and heating values for common tree species are shown in Table 1 (7). Carbon, hydrogen, and oxygen are the elements present in the largest amounts. The heating value of resin-free, moisture-free wood is about 19.3 MJ/kg, while that of resin is about 39.3 MJ/kg. Thus, the woods containing resins or oils (e.g., Douglas-fir and southern pines) have slightly higher heating values than those that do not contain appreciable amounts of these materials (e.g., hemlock, beech, or oak) (7). The composition of other materials besides wood (e.g., shrubs and grasses) in general is similar to the composition of wood. A typical ultimate analysis and heating value for straw (15) is given in Table 1 for comparison.

TABLE 1. ELEMENTAL COMPOSITION AND HEATING VALUE OF VARIOUS TREES (7)[a]

Species	Composition, %						Heating value, MJ/kg
	Carbon	Hydrogen	Oxygen	Sulfur	Nitrogen	Ash	
Douglas fir:							
Wood	52.3	6.3	40.5		0.1	0.8	21.0
Bark	53.0	6.2	39.3			1.5	22.8
Western hemlock:							
Wood	50.4	5.8	41.4	0.1		2.2	21.6
Bark	51.2	5.8	39.2		0.1	3.7	21.6
Yellow pine wood	52.6	7.0	40.0			1.3	22.3
Southern pine bark	56.5	5.5	37.0		0.4	0.6	21.8
Beech wood	51.6	6.3	41.5			0.6	20.4
Red oak wood	49.5	6.6	43.7			0.2	20.2
Straw[b]	42.7	5.9	45.1		0.6	5.6	14.9[c]

[a] Dry basis.

[b] From Reference 15.

[c] Heating value at 15.75% moisture content.

Note: Blanks indicate elements are below detection limit for species shown.

In addition to the major elements listed in Table 1, trace quantities of numerous other elements have been identified in tree

(15) Johnson, A. J., and G. H. Auth. Fuels and Combustion Handbook. McGraw-Hill, New York, New York, 1951.

parts. Table 2 contains a list of some of these elements and their concentrations for various tree types as found in tree bark (16).

TABLE 2. TRACE ELEMENTS MEASURED IN BARK FROM TREE BRANCHES OF DIFFERENT SPECIES (16) (AVERAGE VALUES ON A DRY WEIGHT BASIS)

Species	Alumi-num, ppm	Boron, ppm	Calcium, %	Copper, ppm	Iron, ppm	Magne-sium, %	Manga-nese, ppm	Molyb-denum, ppm	Phos-phorus, %	Potas-sium, %	Zinc, ppm
Red spruce	89	14	1.06	14	124	0.08	834	6.7	0.06	0.15	72
Balsam fir	154	13	0.84	9	162	0.08	77	5.5	0.11	0.36	66
Hemlock	130	18	1.39	9	146	0.08	1,223	8.7	0.10	0.19	41
White pine	157	14	0.83	7	111	0.11	319	5.1	0.07	0.24	94
Northern white cedar	85	9	2.28	1	122	0.07	19	16	0.04	0.05	21
White birch	24	12	1.05	7	38	0.05	235	6.3	0.04	0.10	100
Red maple	23	17	1.38	8	62	0.05	732	7.5	0.07	0.24	70
Aspen	15	14	1.18	12	80	0.09	140	6.4	0.04	0.20	97

Bone-dry wood is composed of cellulose, hemicellulose, lignin, and extractables (oils, pigments, minerals). Cellulose, hemicellulose, and lignin constitute 90 to 95 percent of the weight of the wood. The proportions of these groups in the wood vary from species to species, between trees of the same species, and within parts of the same tree. The organic fraction of the extractables consists of many classes of compounds: aliphatic and aromatic hydrocarbons, alcohols, aldehydes, gums, and sugars (17).

Combustion Process

The burning of wood is accomplished by a two-staged process of pyrolysis and combustion, the relative proportions of which are determined by burning conditions (16). Pyrolysis is generally believed to be a heat-induced, endothermic chemical degradation process in which virgin wood is transformed into charcoal, organic tars, and vapors. Combustion is the subsequent rapid oxidation of the pyrolysate vapors escaping from the surface of the fuel in the presence of oxygen. Although both pyrolysis and combustion occur simultaneously in moving fires, the former is the initiating stage of chemical decomposition. As wood is heated, volatile components move to the fuel surface and are released to the surrounding air. Initially, these volatiles contain large amounts of water vapor and lower molecular weight organic compounds. As temperature increases, the wood material undergoes pyrolytic decomposition. The amount of resulting products depends

(16) Young, H. E. Preliminary Estimates of Bark Percentages and Chemical Elements in Complete Trees of Eight Species in Maine. Forest Products Journal, 21(5):56-59, 1971.

upon heating temperatures, rate of heating, surrounding medium, and wood species.

The order of decomposition of the wood components is: hemicellulose, cellulose, lignin. Extractables evolve on the basis of their volatility and reactivity at the higher temperatures. The classic concept is one of initial heating resulting in an endothermic reaction. Additional heating then results in an exothermic reaction (280°C to 300°C) with liberation of carbon dioxide, carbon monoxide, and liquid distillate (acetic acid and its homologs, methanol, and light tars). Further high-temperature heating results in the production of hydrogen and heavy tars (17).

Hot gases and vapors, once released, mix with the oxygen in the air and ignite - producing a second phase in the combustion process. In this second phase, rapid oxidation, or flaming, of these combustible vapors results in rapidly rising temperatures. Pyrolysis continues during this period, along with the evolution of high concentrations of organic compounds. Some of the pyrolytic proucts cool and condense without passing through the flame zone; others pass through the flames but only partially oxidize, producing a range of products.

Once the fire is started, it is propagated in a series of ignitions. Heating of the fuel ahead of the flame as it progresses is the first step of the flame propagation mechanism. Heat supplied to the potential fuel from the fire dehydrates the surface of the fuel. Further heating results in pyrolysis and the release of combustible gases (as described above), which are then ignited by the flame, and the fire advances to the new position. Finally, a relatively constant rate of spread is achieved, a rate that is the average of all the elemental rates (18).

The above discussion describes mechanisms involved in the active burning phase or advancing front stage of the total prescribed burning process. This phase of the burning process is associated with the visible flame front moving through the fuel. After the main flame front has passed over the fuel, the remaining unburned fuel smolders while dehydration, pyrolysis, solid oxidation, and scattered flaming continue simultaneously. The

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(17) Yamate, G. Development of Emission Factors for Estimating Atmospheric Emissions from Forest Fires. EPA-450/3-73-009 (PB 230 689), U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, October 1973. 127 pp.

(18) Rothermel, R. C. A Mathematical Model for Predicting Fire Spread in Wildland Fuels. Forest Service Research Paper INT-115 (PB 210 095), U.S. Department of Agriculture, Ogden, Utah, January 1972. 40 pp.

smoldering phase, often characterized by emissions of large amounts of smoke, continues as long as temperatures remain adequate.

Firing Techniques

The firing techniques employed in prescribed burning depend on the kind of area to be burned and the burning conditions. There are four major burning techniques: backing fire, heading fire, ring fire, and area-ignition (or sometimes, simultaneous area-ignition) (9). Often, combinations of these categories are used in a single burning operation. A fifth category is that of pile and windrow fires.

Backing Fire--

Backing fires are ignited on the downwind side of an area and permitted to spread against the wind. The advance of the active burning zone is slow, and most of the fuel is consumed within this zone. In this way, smoldering time for the fuel is reduced, and total combustion efficiency of the fire is increased (i.e., for vegetative fuel, the greater the proportion of CO_2 and H_2O produced by the fire, the greater is the combustion efficiency). Since burning on slopes has an effect similar to wind on rate of fire spread, daytime down-slope fires in hilly terrain behave similarly to backing fires in flat country.[a]

The backing fire produces the least fire intensity of all techniques - having slow spread rates, a narrow burning zone, and short flames (5). It therefore lends itself to use in heavy fuel accumulations and in removing understory growth and debris where an overstory of crop trees exists.

Heading Fire--

Heading fires are ignited on the upwind side of an area and spread with the wind. The active burning zone moves rapidly from fuel element to fuel element. Under these conditions, many fuel elements are not consumed completely in the active burning zone. A rather large zone of smoldering fuel is left behind, producing large quantities of products of incomplete combustion. This technique is employed in lighter fuels if the amount of heat produced will not scorch overstory tree crowns. Perennial grasses are more apt to survive heading fires than backing fires. Heading fires are also preferred for control of brownspot disease in longleaf pine.

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[a] Fires set at the base of a slope, and with enough intensity to partially overcome normal nighttime downslope winds, may be made to spread upslope and behave like backing fires. When the nighttime winds are fully overcome in these situations, fires will spread upslope and behave like heading fires.

Ring Fire--
Ring firing is accomplished by igniting the perimeter of the intended burn area and allowing the fire to burn towards the center. This technique results in a rapid, relatively hot fire and finds particular application in reducing timber-harvesting residues in clearcut areas.

Simultaneous Area Ignited Fire--
Area-ignited fires are set by igniting the intended burn area in many individual spots and allowing individual fires to burn in all directions as they come together.

This type of fire is frequently employed in clearcut areas when a rapidly-developed and high-rising convection column is desired. It will have high variability in burning intensity as junction zones of increased intensity form.

Pile and Windrow Fire--
Piles and windrows are used in management programs to effect more complete consumption of large pieces of material, such as logging residue. When hand-piling is practiced (often where timber harvesting has taken place on fragile soils, as in many helicopter logging operations), the objective is to dispose of only the fine fuels and the smaller diameter branchwood. The preferred firing technique calls for igniting the finer fuels around pile perimeters to obtain rapid heat buildup, permitting the larger fuel elements to become ignited and consumed. The extreme fire intensity may adversely affect the soil immediately beneath piles. In occasional, poorly conducted operations, piles and windrows may contain large amounts of soil when machine piled. This may result in areas which burn and smolder for days.

Other Factors Affecting Emissions

In addition to the firing techniques mentioned above, other factors affecting the completeness of burning and emission of pollutants can be separated into the two categories listed below; the factors of major importance are indicated by an asterisk (5).

- Environmental factors
  *wind speed and direction
  *rainfall history
  *relative humidity
  cloud cover
  temperature
  air mass stability
  slope of land

- Fuel conditions
  *fuel moisture content
  *fuel loading
  fuel arrangement
  fuel species composition

Certain of these factors are discussed in more detail in Section 5.

Transport and Diffusion

Downwind concentrations of emissions from the prescribed fire source are a result of the same transport and diffusion processes modeled for other sources, but certain initiating factors require special adaptations.

Because prescribed fires occur over a sizable area, receptor area concentration patterns do not resemble those of stationary sources (such as a stack) except after long travel distances. The point source definition, thus, does not fit well. A better overall definition is as a moving line or as an area source. It must be emphasized, however, that unlike conventional line or area sources, prescribed fires release sufficient heat during initial stages to result in significant, though variable, plume rise. This means that, aside from transport by winds, dispersion of smoke from prescribed fires is a result of three separate mechanisms. The first two mechanisms are entrainment by convection into the rising plume, with subsequent dispersion in the atmosphere. The third mechanism is diffusion of the unentrained portion along the ground. All three mechanisms must be accounted for in predicting the ground level concentrations of pollutants downwind from the source (9).

Plume rise from prescribed fires depends upon the source heat release rate and upon ambient meteorological conditions (chiefly, wind speed and air mass stability). Heat release rate is a function of the amount of fuel being consumed, and differs between fire phases. A fire may be separated into two phases: convective lift phase and no-convective-lift phase. During the convective-lift fire phase, most emissions are entrained into a definite convective column as a result of the large quantities of heat being released. The no-convective-lift fire phase occurs when the heat release rate is not high enough to generate a significant column. The advancing front, or active-burning stage, produces the heat that is responsible for the convective column. Hence, the emissions from this stage are generally contained within the convection column. The residual, or smoldering, combustion stage lacks the necessary heat to produce a significant convection column. As the flaming front of a fire advances, the heat of the front exerts lessening influence on emissions from residual

burning. These residual emissions are less and less drawn into the column, and are increasingly left with no significant plume rise.

There are still important knowledge gaps for the variety of fuel and fire types concerning (1) differing emission rates for the advancing-front fire stages and the residual, or smoldering stages; and (2) heat release rates for these two stages. Thus, a mathematical predictive model of the vertical profile of concentrations in the prescribed fire smoke column is not yet possible. Estimated ratios of amounts of smoke lofted to amounts left unentrained are used instead for the convective lift fire phase. In high-intensity fires, this ratio may attain 100 percent lofted:0 percent unentrained. In low-intensity fires, such as are used under tree canopies in the South, the ratio of 60 percent lofted:40 percent unentrained has been suggested (9). This implies a need to relate these ratios to the amounts of heat released at different times in the life of a fire in order to predict downwind concentrations (19).

FUEL CATEGORIES AND PREFERRED FIRING TECHNIQUES RELATED TO SMOKE PRODUCTION AND DISPERSAL

Percents of net fuel consumed on all ownerships, nationally, have been determined for different categories of fuel in a recent U.S. Forest Service survey (20), as shown in Figure 2. Preferences for firing techniques were determined in the same survey. In this section, major fuel categories and preferred firing techniques are discussed in relation to smoke production and dispersal. Geographic distributions of these same major fuel categories are covered in Section 4.

Piled or Windrowed Timber Harvesting and Land-Clearing Residues

Net national total fuel consumption is 17.9×10^6 metric tons, dry weight. Two subcategories of piled or windrowed timber harvesting and of landclearing residues have been combined due to the relatively low amounts reported for all lesser categories of landclearing (less than 3 percent of the national total net fuel consumed in all, including rights-of-way, brushfields, and open range). While practiced in the East, the greater extent of this

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(19) Lavdas, L. G. Plume Rise from Prescribed Fire. In: Proceedings of the Society of American Foresters/American Meteorological Society 5th Conference on Fire and Forest Meteorology, Atlantic City, New Jersey, 1978. pp. 88-91.

(20) Pierovich, J. M. Office Report: A National Survey of Prescribed Burning and Managed Natural Fires on All Ownerships. Unpublished report on file, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, 1978. 19 pp.

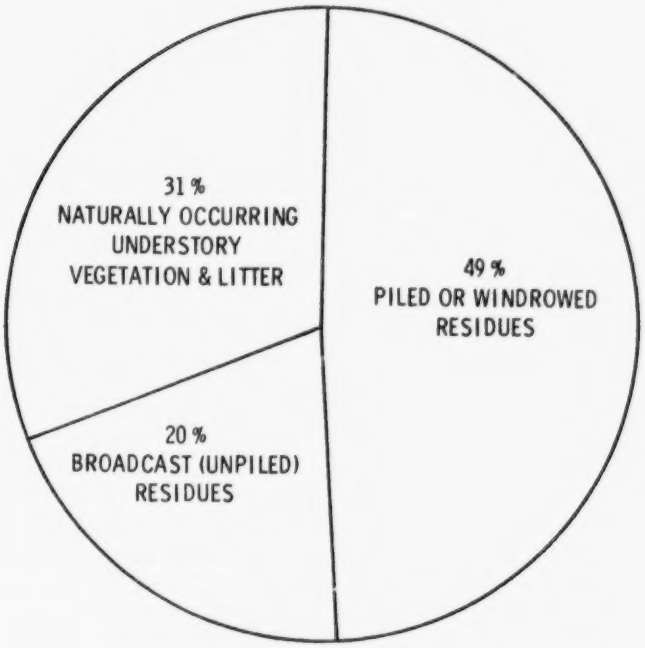

Figure 2. Extent of burning by categories of fuel, expressed as percents of national total fuel consumed each year (20).

type of burning is in the states west of the Mississippi River. Investment in piling or windrowing treatment prior to burning is for two main purposes: (1) to provide more unimpeded access for subsequent revegetation or tree planting (usually by machines) and use (as for grazing animals), and (2) to promote more efficient combustion of larger materials. Stumps and root crowns are included in some road right-of-way clearing, where forced air blowers may even be employed to accelerate fuel consumption, and in some range improvement where groups of dwarfed trees (frequently piñon and juniper) are uprooted by cabling as a means of returning the landscape to a more open savannah type.

The firing technique preferred for this category is from the base of the pile or windrow, and is obviously one which will provide as rapid ignition throughout as possible. In this way, advantage is taken of radiant heat for more complete combustion and greater convective lift of the smoke. As a general rule, the dryer the material, the larger the pile dimensions, the greater proportion of small sizes to be burned, and the less soil mixed in with the fuel, the more complete will be the combustion. It follows that the more rapid and complete the combustion, the less unwanted emissions and the greater the convective lift of the smoke plume.

In partially-cut timber stands, piled harvesting residues are confined to smaller quantities in each pile, but these are frequently only limbwood and often are hand piled. Smaller piles will be less likely to scorch tree crowns and are best suited to the scattered residues being treated. Often, the piles are covered to keep out rain, and then burned in late season when the surrounding forest is wet or snow covered. Soil mixed with material to be burned is usually minimal. An opportunity presents itself with this treatment to schedule burning days for optimum atmospheric dispersion and to limit amounts burned on any one day.

In areas where the entire stand has been harvested ("clear-cut"), larger machine-constructed piles or windrows are employed. On steep slopes (>30%), piles are frequently made using cable systems, and sometimes helicopters, to bring the material to the collection and loading point ("landing") of the preceding harvesting operation. This practice, which results in very little soil disturbance, has come to be known as "*YUM*" for yarding (collection) of unmerchantable material. In the Northwest, where this practice was undertaken by some land managers in an attempt to better meet air quality requirements, the *YUM* piles are sometimes sold for further utilization, depending upon markets, and are looked upon as a potential new source of energy. This practice is in itself energy-demanding, and the additional operating fuel costs for loading, hauling, and further preprocessing can result in a negative energy balance. Piles which are not further utilized are available for burning late into the rainy season and are sometimes even burned during precipitation as a means of "washing out" the emissions.

In more gentle terrain, piling and windrowing in clearcut areas are more likely to be done by bulldozers with brush-rake blades (specially designed to minimize soil admixtures). This practice is employed, rather than burning the material in place, where it is desired to maximize the cleared area available for reforestation. The benefits are that on the flatter sites, machine planting is facilitated, and young trees are less subject to sustained heat from large logs if wildfires later burn into planted areas. The detriments are that greater soil disturbance may occur and that more care must be taken to avoid soil admixtures with fuels to be burned. As a consequence of windrowing, large dimension material is afforded a greater opportunity to become better ignited than if burned in place (broadcast treatment), but is not afforded the desirable sustained heat of larger piles.

Naturally Occurring Understory Vegetation and Litter

Net national total fuel consumption is 11.5 x 10^6 metric tons, dry weight. Understory burning may be for one land management objective in particular, with fire prescriptions written to promote this benefit most, but other objectives are usually met as

well. More common objectives are for fuel hazard reduction, wildlife habitat improvement, forage improvement, disease control (as discussed earlier in particular for control of brownspot disease in longleaf pine during the "grass stage" of growth development), and improved access. The practice is most common in the coastal plain of the Southern States, but is being extended north and west wherever natural fire dependence is recognized for the desired dominant species. Common names of principal species in fuel associations where this practice is employed are as follows: in the East, in descending order of importance, southern pine, southern pine/hardwood, jack pine/red pine, oak/pine;in the West, in descending order of importance, ponderosa pine, Douglas-fir/mixed conifer, mixed conifer, aspen.

Preference for firing technique varies widely with individual dominant species and even within species as influenced by fuel continuity, and probably as influenced by experience with an established technique for a local area. Overall preferences, based upon amounts of net fuel consumed, are backing fires in multiple strips in both the East and West. General preferences for other firing techniques, in descending order, are then as follows: in the East, backing fires in a single line of fire, heading fires in a single line of fire, heading fires in multiple strips; in the West, heading fires in multiple strips, backing fires in a single line of fire, heading fires in a single line of fire. An increasing emphasis is being given to development of ignition methods for closely-spaced simultaneous area ignition, and a trend to this technique may be expected.

Because the foremost requirement of all understory burning is to avoid scorched foliage in tree crowns (a general rule being the less the better, but always to protect at least the upper two-thirds of crown), fires in this fuel category are intentionally of low intensity. Enough surface wind must also be present to disperse the heat from under the timber stand.

Backing fires are less intense than other firing techniques. Backing fires move slowly against the wind and/or downslope, and will assure the most complete fuel consumption, but, as will be discussed further in Section 5, they may result in a contrast of emission products.

Heading fires are more intense, move rapidly with the wind and/or upslope, and usually consume less fuel. Their combustion efficiency is also less than backing fires, and, thus, characteristically large smoldering areas are left behind the flaming front. Plumes of heading fires are apt to be darker in appearance because of a greater tendency toward "soot" production during the hotter flaming period. Since heat is given off rapidly, the plume will be lofted well during the convective-lift fire phase, but it is

during the non-convective-lift phase that smoke from the remaining smoldering fuel will not be well lofted because of a low heat-release rate.

For maintenance of acceptable levels of fire intensity, simultaneous area ignition in underburning will depend upon numerous small heading fires burning rapidly together. Because this technique is still mainly under development, emissions and heat release rates have not been studied to date. It can be expected, however, that emissions will correspond to heading fires and that the greater concurrent heat release during flaming combustion will tend to add to plume height.

Broadcast (Unpiled) Timber-Harvesting and Land-Clearing Residues

Net national total fuel consumption is 7.2×10^6 metric tons, dry weight. As with piled and windrowed fuels, broadcast (unpiled) timber-harvesting and land-clearing residues have been combined in one category because of the relatively low amounts reported for brushfields and open-range treatments (less than 2 percent of the reported national total net fuel consumed). Included in this category of fuel is an unreported amount of residues which are pretreated in place by a practice known as "chopping." When pretreated in this way (commonly using tractor-drawn bladed rollers), tops and limbwood are broken and crushed into a more compact fuel arrangement, which can be expected to result in less flashy combustion, as well as in better fuel consumption (provided the chopping is done when soil conditions resist burying and soil admixtures with the fuel to be burned). No known emissions studies have been conducted in this special fuel type which is mostly limited to more gentle terrain in the East and to certain brushfield and open-range treatments in the West.

As part of understanding treatment of this category of fuel, it must be recognized that a substantial amount of timber-harvesting residues are left broadcast but unburned. As examples, this may occur when land managers determine that a fire risk is low or that soils on fragile slopes will benefit most from permitting the woody material to decay in place.[a]

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[a]Criteria for such decisions are given in Reference 21, pp. 213-217.

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(21) Pierovich, J. M., et al. Forest Residues Management Guidelines for the Pacific Northwest. Forest Service General Technical Report PNW-33, U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, 1975. 273 pp.

Areas of broadcast residue fuels designated for prescribed fire treatment include those where there is an overstory of trees, those where there has been no tree overstory (e.g., brushfields or large areas of grassland) and those where all standing trees have been harvested ("clearcut").

When an overstory is present, low-intensity fires are prescribed, just as in the previously described treatment of naturally-occurring understory vegetation and litter. Only an estimated one percent of the national total net fuel consumed is in this subcategory, mainly in the selectively harvested ponderosa pine, mixed conifer, and lodgepole pine stands of the West. Preferred treatments, when under a timber stand, are for strips of backing fires, single lines of backing fires, and strip-heading fires, in descending order of preference. Smoke production and dispersion relationships are similar to these same firing techniques when applied to understory vegetation and litter, except that harvesting residues result in longer times both for flaming combustion and for smoldering combustion during the non-convective-lift fire phase. Diurnal weather changes are, thus, of great importance in planning this technique for disposal of harvesting residues.

Preferred firing techniques for broadcast residues not under a timber canopy favor more intense fires. The extent of larger materials consumed depends upon fuel moisture and the extent to which these have become accumulated in one place (or as popularly described, "in jackpots") during previous harvesting operations. Because aerial seeding and hand-planting or natural regeneration, rather than machine operations, are practiced on most such areas, burning is conducted mainly to reduce only branchwood and other residues smaller than 2 inches in diameter. Frequently, larger logs are consumed only when they are decayed, or when concentrations of pitch are present. Where there is no overstory of trees, firing techniques in descending order of reported preference for broadcast residues treatment are: single lines of heading fires (usually with a backing fire set first as a control measure at the top of the slope or on the downwind boundary); strips of backing fires; ring fires (where the order of firing calls for progression from the upslope or downwind boundary, along both flanks, and then across the base of the slope or upwind boundary); simultaneous area ignition; strips of heading fires; single lines of backing fires.

Correspondence to each of the firing techniques described previously for other fuel categories are apparent. The ring fire technique is most similar to several heading fires burning toward a common central point and with a common well-defined smoke plume

during the convective-lift fire phase. It has been postulated (22) that the time relationships of emissions for a representative prescribed fire in this fuel category in Western Oregon and Washington are constant for the first 6 hours, then undergo exponential decay with a 4-hour time constant. Significant plume rise has been further hypothesized to occur during the first 4 hours, with 100 percent lofting of emissions assumed for calculations covering this time period.

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(22) Lavdas, L. G. A Statistical/Physical Estimate of the Effect of Western Oregon Burning on Willamette Valley Air Quality. Unpublished manuscript in progress, copy on file, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, 1979. 15 pp.

SECTION 4

GEOGRAPHIC DISTRIBUTION OF FUELS BURNED BY PRESCRIPTION

The U.S. Forest Service survey of all ownerships (20) referenced in Section 3 was conducted among field offices, extending in some cases to the district organizational level of the agency and its cooperators. In other cases, estimates were made from available data at regional levels only. Data have been summarized for the geographic regions delineated in Figure 3, and for the Alaska Region which is not shown.

Net total amounts of fuel consumed (i.e., "available fuel") reported in each of the fuel categories described in Section 3 are shown by geographic regions in Table 3. The estimated total annual fuel consumption of 3.66×10^7 metric tons exceeds previous estimates by more than 100%. For example, a national inventory of forest wildfires, forest managed burns, and agricultural burns reported a fuel consumption for managed burns of 1.56×10^7 metric tons (23). An increase in amounts over previous estimates is perhaps most due to estimates of additional acreages of burning done on private lands, but estimates of tons of fuel burned per acre are also subject to variability. Methods are available by which fairly exacting fuel estimates can be made, but these are often expensive; in the present survey, most estimates were limited by cost and time constraints to experienced judgments. These judgments are likely least accurate for the broadcast timber harvesting and land clearing fuel category.

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(23) Yamate, G. Emissions Inventory from Forest Wildfires, Forest Managed Burns, and Agricultural Burns. EPA-450/3-74-062 (PB 238 766), U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, November 1974. 34 pp.

Figure 3. Geographic regions used to summarize survey data within the conterminous states. (Alaska Region also used in summarization not shown.)

TABLE 3. ESTIMATED NET TOTAL WEIGHTS OF FUEL CONSUMED ANNUALLY IN PRESCRIPTION BURNING ON ALL OWNERSHIPS (20)

Geographic region	Net annual consumption, 10^5 metric tons (dry weight)			
	Timber harvesting and land clearing residues		Naturally occurring understory vegetation and litter	Total of all categories
	Piles or windrows	Broadcast (unpiled)		
Alaska	0.5			0.5
Eastern	0.1	0.3	0.1	0.5
Intermountain	6.9	0.7		7.6
Northern	82.7	6.3		89.0
Pacific Northwest	50.4	37.0		87.4
Pacific Southwest	20.2	8.2[a]	0.5	28.9
Rocky Mountain	4.9[a]	1.0	0.2	6.1
Southern	0.9	9.9	114.2	125.0
Southwestern	12.3	8.3[a]	0.3	20.9
Total of all regions	178.9	71.7	115.3	365.9

[a] Includes precommercial thinning residues as follows: Pacific Southwest and Rocky Mountain, each $<0.1 \times 10^5$ metric tons; Southwestern, 1.1×10^5 metric tons.

Table 3 shows that prescribed fire treatment of the Naturally Occurring Understory Vegetation and Litter fuel category is dominant both nationally and regionally in the Southern Region. While western regions are presently reporting relatively low amounts in this fuel category, an expected upward trend will be discussed later in Section 7 of this report. The conversion of old growth (i.e., virgin) forests to managed forests accounts for much of the relatively greater amounts of Timber Harvesting and Land Clearing Residues categories of fuel consumed in the western regions.

It is useful to examine the relative importance of prescribed burning by regions of the Nation. Relative importance is shown by regions in Figure 4 as percents of net national total fuel consumed. Three regions are seen in Figure 4 to account for 82 percent of the national total net fuel consumed.

Prescription burning is possible only when both weather and fuel moisture variables are within prespecified ranges. Increased attention to optimizing atmospheric dispersion has placed a new dimension on weather variables. As discussed in Section 3, piled and windrowed fuels can often be burned when other fuels are too moist, or even when the forest is blanketed by snow. No attempt is made here to assess the days available to burning when all variables are within prescribed ranges or at optimums, but information from the referenced survey does make possible a statement of the seasonal climatologies that are needed for this purpose, as well as for the purpose of determining downwind impacts.

Seasons of burning for the principal species in each fuel association are given in the series of Tables 4a through 4i, each of which covers a specific geographic region. Fuel associations in the Table 4 series are presented in descending order of importance (on the basis of net total weight of fuel consumed) for each region.

Many land managers routinely employ a National Fire Danger Rating System (24) in planning their daily fire management activities. A series of indices in this system provides needed information about the day's predicted fire business. The system also affords a now limited number of stylized fuel models with which many land management personnel are familiar. Those NFDRS fuel models reported to be applied within each fuel association are, thus, also listed in descending order of importance (fuel consumed basis) in the Table 4 series. With this information available,

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(24) Deeming, J. E., R. E. Burgen, and J. D. Cohen. The National Fire Danger Rating System. Forest Service General Technical Report INT-39, U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, 1978. 63 pp.

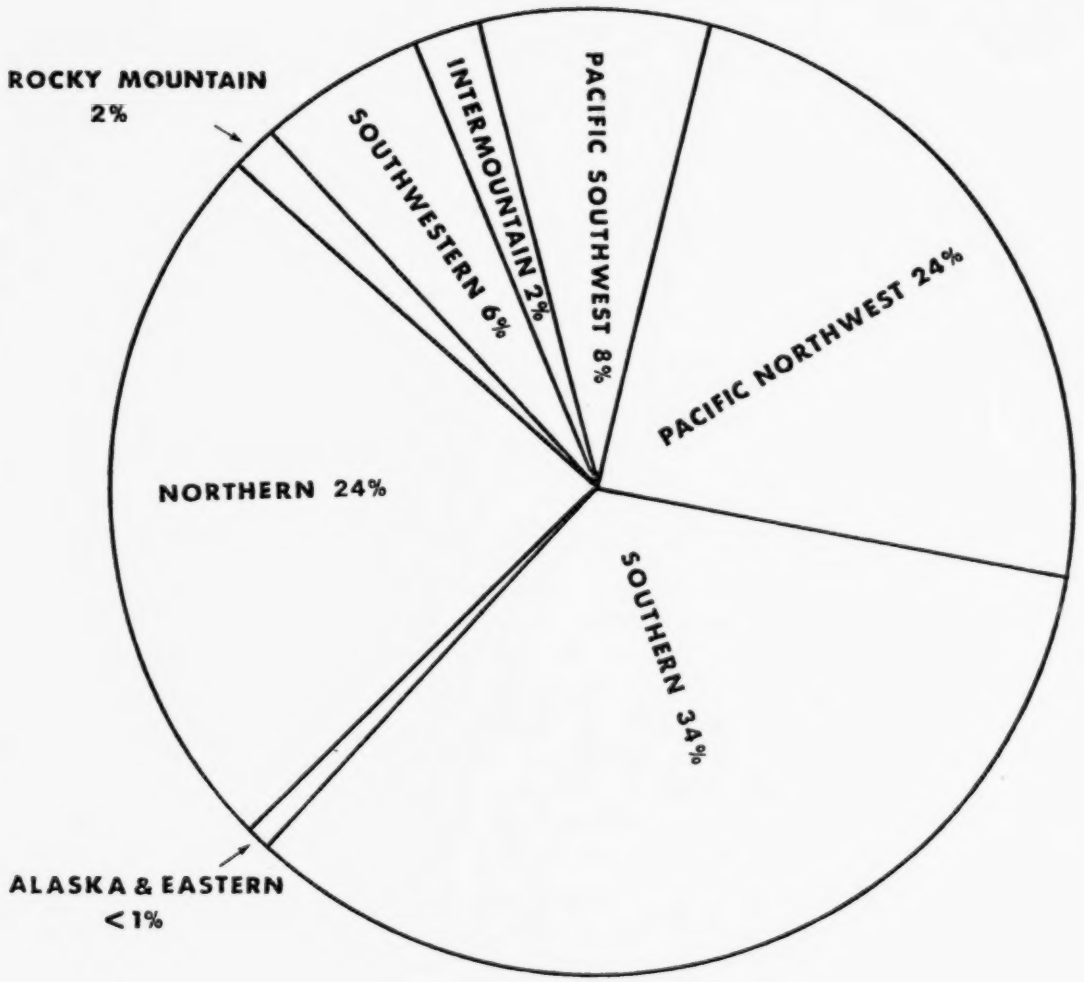

Figure 4. Extent of prescribed burning programs by geographic regions, expressed as percents of national net total fuel consumed each year, all ownerships (20).

TABLE 4a. SERIES OF GEOGRAPHIC REGION TABLES SHOWING THE PRINCIPAL SPECIES, NATIONAL FIRE DANGER RATING FUEL MODELS (NFDRS) APPLIED, AND BURNING SEASONS FOR EACH GEOGRAPHIC REGION... ALASKA REGION (20)

Common names of principal species in fuel association	NFDRS fuel model	Burning seasons											
		JA	F	MR	AP	MY	JN	JY	AU	S	O	N	D
White spruce and white spruce/birch	I		/———	———	———	———/					/———	———	———/

TABLE 4b. SERIES OF GEOGRAPHIC REGION TABLES SHOWING THE PRINCIPAL SPECIES, NATIONAL FIRE DANGER RATING FUEL MODELS (NFDRS) APPLIED, AND BURNING SEASONS FOR EACH GEOGRAPHIC REGION... EASTERN REGION (20)

Common names of principal species in fuel association	NFDRS fuel model	Burning seasons											
		JA	F	MR	AP	MY	JN	JY	AU	S	O	N	D
Species comprising ~90% of reported net total fuel consumed													
Jack pine	K	/———	———	———	———	———/				/———	———	———	———/
	J						/———	———	———/				
Jack pine/red pine	J			/———	———	———	———	———	———	———	———	———	———/
Southern pine	H & K		/———	———	———	———/							
Oak	E										/———	———	———/
Remaining species comprising ~10% of reported net total fuel consumed													
Aspen/balsam fir	E				/———	———/	/———	———	———/				

TABLE 4c. SERIES OF GEOGRAPHIC REGION TABLES SHOWING THE PRINCIPAL SPECIES, NATIONAL FIRE DANGER RATING FUEL MODELS (NFDRS) APPLIED, AND BURNING SEASONS FOR EACH GEOGRAPHIC REGION... INTERMOUNTAIN REGION (20)

Common names of principal species in fuel association	NFDRS fuel model	Burning seasons JA	F	MR	AP	MY	JN	JY	AU	S	O	N	D
Species comprising ∿90% of reported net total fuel consumed													
Lodgepole pine	H				/—	——	——	——	——	——	——	—/	
	G								/—	——	—/		
	C								/—	——	——	—/	
	I									/—	——	—/	
Douglas-fir	H & J									/—	——	—/	
	I								/—	——	——	—/	
	C					/—	—/			/—	——	—/	
Lodgepole pine/ mixed conifer	G			/—	—/					/—	—/		
	C			/—	—/								
	H									/—	——	—/	
Mixed conifer	I					/—	—/						
Engleman spruce/fir	I								/—	—/			
	H			/—	——	——	——	——	——	——	——	—/	
	G									/—	—/		
Ponderosa pine										/—	——	—/	
Remaining species comprising ∿10% of reported net total fuel consumed													
Ponderosa pine/ mixed conifer	I									/—	—/		
	C									/—	——	—/	
Piñon/juniper	C									/—	——	—/	
	H										/—	—/	
Aspen	C									/—	——	—/	
Grass	C					/—	——	——	——	——	——	—/	
Grass/sagebrush	C					/—	—/			/—	——	—/	
Sagebrush/bitterbush/ greasewood	C					/—	——	——	——	——	——		
Sagebrush/piñon/ juniper	D						/—	——	——	—/			

TABLE 4d. SERIES OF GEOGRAPHIC REGION TABLES SHOWING THE PRINCIPAL SPECIES, NATIONAL FIRE DANGER RATING FUEL MODELS (NFDRS) APPLIED, AND BURNING SEASONS FOR EACH GEOGRAPHIC REGION... NORTHERN REGION (20)

Common names of principal species in fuel association	NFDRS fuel model	Burning seasons											
		JA	F	MR	AP	MY	JN	JY	AU	S	O	N	D
Cedar/hemlock/grand fir/lodgepole pine/ Douglas-fir/larch/ mixed conifer	I	/—/				/———	———	———	———	———	———	———/	/—/

TABLE 4e. SERIES OF GEOGRAPHIC REGION TABLES SHOWING THE PRINCIPAL SPECIES, NATIONAL FIRE DANGER RATING FUEL MODELS (NFDRS) APPLIED, AND BURNING SEASONS FOR EACH GEOGRAPHIC REGION... PACIFIC NORTHWEST REGION (20)

Common names of principal species in fuel association	NFDRS fuel model	Burning seasons											
		JA	F	MR	AP	MY	JN	JY	AU	S	O	N	D
Douglas-fir/hemlock/ cedar/spruce/ Ponderosa pine/ mixed conifer	I	/———	———	———	———	———	———	———	———	———	———	———	———/

Note: Burning season, though year-long largely as a result of piling, usually peaks for: Coast Range in late spring; Cascades and Eastern portions in fall.

TABLE 4f. SERIES OF GEOGRAPHIC REGION TABLES SHOWING THE PRINCIPAL SPECIES, NATIONAL FIRE DANGER RATING FUEL MODELS (NFDRS) APPLIED, AND BURNING SEASONS FOR EACH GEOGRAPHIC REGION... PACIFIC SOUTHWEST REGION (20)

Common names of principal species in fuel association	NFDRS fuel model	Burning seasons JA	F	MR	AP	MY	JN	JY	AU	S	O	N	D
Species comprising ~90% of reported net total fuel consumed													
Mixed conifer	Not specified										/——/		
	J&K comb.	/———	———	———	———	———	——/			/———	———	———	/——/
	I					/——	—/				/———		
	C				/———	———	——/						
	K	/———	———	———	———	———	——/				/———		
	J									/———	—/		
Mixed conifer/ Douglas-fir	I&J comb.	/———	———	———	———	——/							
Douglas-fir	Not specified		/——	—/							/——	—/	
	I								/———	———	———	———	/——/
Chaparral and Chamise/chaparral	Not specified	/———	———	———	———	——/						/——	—/
	F	/——	—/									/——	—/
Remaining species comprising ~10% of reported net total fuel consumed													
Ponderosa pine	K			/———	———	——/							
Ponderosa pine/ Douglas-fir	J		/———	———	———	——/							
Piñon/juniper	K		/———	———	———	———	———	——/					

TABLE 4g. SERIES OF GEOGRAPHIC REGION TABLES SHOWING THE PRINCIPAL SPECIES, NATIONAL FIRE DANGER RATING FUEL MODELS (NFDRS) APPLIED, AND BURNING SEASONS FOR EACH GEOGRAPHIC REGION... ROCKY MOUNTAIN REGION (20)

Common names of principal species in fuel association	NFDRS fuel model	Burning seasons JA	F	MR	AP	MY	JN	JY	AU	S	O	N	D
Ponderosa pine	C			/———	———	——/					/———	——/	
	K	/—/							/———	———	———	———	/——/
Lodgepole pine	J			/———	———	——/				/———	———	———	/——/
Engleman spruce	K				/——	—/				/———	———	—/	
"Brush" (spp. unspecified)	F				/——	—/							

TABLE 4h. SERIES OF GEOGRAPHIC REGION TABLES SHOWING THE PRINCIPAL SPECIES, NATIONAL FIRE DANGER RATING FUEL MODELS (NFDRS) APPLIED, AND BURNING SEASONS FOR EACH GEOGRAPHIC REGION... SOUTHERN REGION (20)

Common names of principal species in fuel association	NFDRS fuel model	Burning seasons JA	F	MR	AP	MY	JN	JY	AU	S	O	N	D
Southern pine	D	/———/										/—/	
	K	/———/								/———/			
	C	/———/										/—/	
Southern pine/ Hardwood	E	/———/								/———/			
	K	/———/										/—/	
	J	/———/							/———/				

TABLE 4i. SERIES OF GEOGRAPHIC REGION TABLES SHOWING THE PRINCIPAL SPECIES, NATIONAL FIRE DANGER RATING FUEL MODELS (NFDRS) APPLIED, AND BURNING SEASONS FOR EACH GEOGRAPHIC REGION... SOUTHWESTERN REGION (20)

Common names of principal species in fuel association	NFDRS fuel model	Burning seasons JA	F	MR	AP	MY	JN	JY	AU	S	O	N	D
Species comprising ~90% of reported net total fuel consumed													
Ponderosa pine	J									/———/			
	K	/—/							/———/				
	J&K comb.	/———/							/———/				
	C	/———/								/———/			
	G									/———/			
Remaining species comprising ~10% of reported net total fuel consumed													
Mixed conifer	G									/———/			
	K											/—/	
Piñon/juniper	C								/———/				

current investigations (25, 26) may lead to ways that the familiar NFDRS can in time be used in a new applied technology for managing prescribed fire emissions. Categories of fuels included in the Fuel Models are listed in Table 5 for additional reference.

Both the National Parks and National Forests are beginning to include areas where fires are permitted to burn under prespecified conditions, in recognition of the natural role of fire in fulfilling ecological requirements. Not included in the preceding figures and tables, this type of "prescribed fire" is coming to be known by several names: "Prescribed Natural Fire;" "Managed Natural Fire;" "Fire by Unplanned Ignitions;" etc. The survey shows that at present such fires account for less than 4/10 percent of all fuel consumed nationally, with most of it being in the western regions.

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(25) McMahon, C. K. Combustion Processes in Wildland Fuels Research Work Unit Description. Unpublished draft on file, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, 1979. 10 pp.

(26) Ryan, P. W. Smoke Management Systems Research Work Unit Description. Unpublished draft on file, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, 1979. 9 pp.

TABLE 5. CATEGORIES OF FUELS ASSOCIATED WITH NATIONAL FIRE DANGER RATING SYSTEM FUEL MODELS (24)

Fuel category	NFDRS model
Grass and grass-like:	
Western annual grasses	L
Western perennial grasses	A
Everglades sawgrass	N
Tundra	S
Savannah:	
Open timber with grass	C
Brush:	
Mature California chaparral	B
Intermediate chaparral	F
High pocosin	O
Southern rough (palmetto-gallberry)	D
Shrubs and grass	T
Timber:	
Short-needled conifer--heavy dead	G
Short-needled conifer--normal dead	H
Southern pine plantation	P
Alaskan upland black spruce	Q
Hardwoods--summer	R
Hardwoods--winter	E
Long-needled conifer--normal dead	U
Slash (timber harvesting residues):	
Heavy	I
Medium	J
Light	K

SECTION 5

EMISSIONS

INTRODUCTION

Although emissions from prescribed fires may be similar to those from other combustion processes, their complete characterization is much more complex. Many parameters affect the type of emissions generated, the magnitude of emissions, and the emission rate; these prameters vary widely from fire to fire. In addition, the techniques used to measure emissions are still under development and rely heavily on simulated fires. Emissions data for prescribed fires are not extensive, especially in view of the many types of prescribed fires, and much more work is needed in the area of emissions measurement. This section discusses the factors that affect emissions from prescribed fires, the techniques used to measure emissions, and the emissions data that have been reported to date. Data have been evaluated in terms of representativeness and reliability by examining test conditions and methods.

TYPES OF EMISSIONS

Emissions from prescribed fires include both criteria and non-criteria pollutants. Criteria pollutants are those for which ambient air quality standards have been set as listed in Table 6 (27-29). Particulate matter includes any condensed phase that can be trapped on a filter at standard conditions of temperature and pressure, excluding water. In some cases, material collected in impingers following the filter may be added into the total particulate loading. For many combustion sources such as utility boilers, particulate emissions are an inorganic ash formed from

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(27) Federal Register, 36:22384, November 25, 1971.

(28) Federal Register, 43:46258, October 5, 1978.

(29) Federal Register, 44:8220, February 8, 1979.

TABLE 6. SUMMARY OF NATIONAL AMBIENT AIR QUALITY STANDARDS (27-29)

Pollutant	Averaging	Primary standards, µg/m³	Secondary standards, µg/m³
Particulate matter	Annual (geometric mean)	75	60[a]
	24-hr[b]	260	150
Sulfur Oxides (measured as sulfur dioxide)	Annual (arithmetic mean)	80	[c]
	24-hr[b]	365	[c]
	3-hr[b]	[c]	1,300
Carbon monoxide	8-hr[b]	10,000	10,000
	1-hr[b]	40,000	40,000
Nitrogen dioxide	Annual (arithmetic mean)	100	100
Ozone	1-hr[b]	235	235
Hydrocarbons (nonmethane)	3-hr (6 a.m. to 9 a.m.)	160[d]	160
Lead	Quarterly	1.5	1.5

[a]The secondary annual standard (60 µg/m³) is a guide for assessing implementation plans to achieve the 24-hr secondary standard.

[b]Not to be exceeded more than once per year.

[c]No standard exists.

[d]There is no primary ambient air quality standard for hydrocarbons. The value of 160 µg/m³ used for hydrocarbons in this report is an EPR-recommended guideline for meeting the primary ambient air quality standard for ozone.

minerals in the fuel. However, particles generated in prescribed fires result from incomplete combustion and are primarily carbonaceous material (30).

Carbon monoxide and hydrocarbons also result from incomplete combustion. Hydrocarbons comprise a great number of individual organic compounds; when used in the context of criteria pollutants, the term denotes total nomethane hydrocarbons as measured by a specified analysis method, namely a flame ionization detector (FID). "Hydrocarbon" is somewhat of a misnomer because oxygenated organic species are measured as part of the total.

Sulfur oxides are formed during combustion by the oxidation of sulfur in the fuel. They are not released to any great extent by prescribed fires because the sulfur content of vegetation is low; typical values are: <0.2% in foliage (30) and <0.1% in branches and wood components (31). Nitrogen oxides arise from nitrogen in the fuel and by reaction of atmospheric nitrogen in the flame zone.

Non-criteria pollutants (i.e.: pollutants for which no ambient air quality standards have been established) emitted from prescribed fires are primarily organic species and trace elements that are considered on an aggregate basis under the criteria pollutant categories of hydrocarbons and particulate matter. They are treated separately here to distinguish their specific environmental effects. One class of organic compounds, the polycyclic organic materials (POM's), includes recognized carcinogens. Known to be formed in virtually all combustion processes involving carbonaceous fuel, their evaluation has been mandated by the Clean Air Act Amendments of 1977.

FACTORS AFFECTING EMISSIONS

Because emissions from prescribed fires are produced during the combustion process, variables that affect combustion are the same as those affecting emissions. This perspective is important in understanding the variability in emissions from prescribed fires. Particulate matter, hydrocarbons, and carbon monoxide emissions from prescribed burning are a result of incomplete combustion. As a simplification, it follows that those factors promoting better combustion tend to reduce emissions of these constituents, and

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(30) Ryan, P. W., and C. K. McMahon. Some Chemical and Physical Characteristics of Emissions from Forest Fires. Presented at the 69th Annual Meeting of the Air Pollution Control Association, Portland, Oregon, June 27-July 1, 1976. 21 pp.

(31) Shriner, D. S., and G. S. Henderson. Sulfur Distribution and Cycling in a Deciduous Forest Watershed. Journal of Environmental Quality, 7(3):392-397, 1978.

vice versa. The actual situation is more complex because some parameters are interdependent, but the general principle applies.

For convenience, the variables affecting emissions can be grouped into three categories: (1) firing techniques, (2) type and condition of the fuel, and (3) environmental factors. Firing techniques have been described in Section 3. One of the more important emissions effects of varying firing technique is between heading fires and backing fires. Heading fires, for example, result in more residual smoldering (a poor combustion situation) and yield approximately three times more total suspended particulate matter than do backing fires (32). Fuel that is piled for burning constitutes a distinct type of combustion situation that has not been adequately characterized. Combustion conditions (e.g., higher flame temperatures and longer burning times) suggest that burning piles may resemble wood burned in fireplaces, but it must be noted that fuel and fire conditions would be expected to be more ideal in fireplaces.

Fuel-related variables play a major role in determining emissions and encompass such items as the type of fuel (this may be quite complex), arrangement of fuel, fuel loading (i.e., amount of fuel per unit area), and fuel moisture content. Fuel type signifies the material burned (wood, brush, grass, leaves, or a combination of these), the plant species, size of fuel pieces (i.e., the length and diameter of pieces of wood), and age. Studies have shown a difference in emissions not only between burning wood vs burning leaves, but also between burning wood of different species (9, 33-36).

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(32) Ward, D. E., C. K. McMahon, and R. W. Johansen. An Update on Particulate Emissions from Forest Fires. Presented at the 69th Annual Meeting of the Air Pollution Control Association, Portland, Oregon, June 27-July 1, 1976. 14 pp.

(33) Snowden, W. D., D. A. Alguard, G. A. Swanson, and W. E. Stolberg. Source Sampling Residential Fireplaces for Emission Factor Development. EPA-450/3-76-010, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, November 1975. 173 pp.

(34) Clayton, L., G. Karels, C. Ong, and T. Ping. Emissions from Residential Type Fireplaces. Source Tests 24C67, 26C, 29C67, 40C67, 41C67, 65C67, and 66C67, Bay Area Air Pollution Control District, San Francisco, California, January 31, 1968. 6 pp.

(35) Butcher, S. S., and D. I. Buckley. A Preliminary Study of Particulate Emissions from Small Wood Stoves. Journal of the Air Pollution Control Association, 27(4):346-347, 1977.

(36) Darley, E. F. Emission Factor Development for Leaf Burning. EPA-450/3-76-004 (PB 263 660), U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1976. 43 pp.

Environmental variables that influence emissions production include wind speed, wind direction with respect to the fire, rainfall history, relative humidity, air temperature, atmospheric stability, and slope of land. Wind speed, wind direction, and slope of land all determine how fast a heading fire or backing fire will spread. In general, a faster moving fire front burns less efficiently, produces more smoldering, and results in higher emission levels. Rainfall history and relative humidity have a direct bearing on the fuel moisture content.

Detailed consideration of some of the variables that affect emissions is presented later under emission data for individual pollutants. It must be emphasized again that the correlations observed between emission levels and various parameters are only generalizations, and can not be expected to apply in every situation.

MEASUREMENT TECHNIQUES

Because prescribed fires are more nearly moving line or area sources than point sources, and lack a convenient stack from which to take samples, it is only with difficulty that emission measurements taken in the field can be related to the actual quantity of fuel consumed. Determining the total fuel consumed in an individual burn is in itself a formidable task. Consequently most emissions studies have relied on laboratory simulation of field conditions. The major drawback to laboratory studies is their inability to reproduce all of the factors present in a field situation. As a result there is uncertainty involved in applying measurements taken in the lab to field conditions, with the degree of uncertainty depending on the fire type being modeled.

Plumes from prescribed fires have been sampled using apparatus on masts, in aircraft, and supported by tethered balloons (37-39).

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(37) Ward, D. E., E. R. Elliott, C. K. McMahon, and D. D. Wade. Particulate Source Strength Determination for Low-Intensity Prescribed Fires. In: Proceedings, Control Technology of Agricultural Air Pollutants Specialty Conference, Air Pollution Control Association, Pittsburgh, Pennsylvania, March 1974. pp. 39-55.

(38) Radke, L. F., J. L. Stith, D. A. Hegg, and P. V. Hobbs. Airborne Studies of Particles and Gases from Forest Fires. Journal of the Air Pollution Control Association, 28(1):30-34, 1978.

(39) Ryan, P. W., C. D. Tangren, and C. K. McMahon. A Balloon System for Profiling Smoke Plumes from Forest Fires. Paper No. 79-6.1, Presented at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, June 24-29, 1979.

A "window" is defined through which the windspeed (air flow) and emissions concentrations are measured; these must then be related back to the originating fire and its rate of fuel consumption at the time of emissions production. Work in progress at the Forest Service Southern Forest Fire Laboratory includes studies which are pointed toward improving upon indirect methods for measurement of combustion rate (39). A unique experiment has also provided results by which aerial and ground sampling systems have been compared (40). Elusive plumes in a varying wind will, however, continue as a persistent field sampling problem best solved by conducting field experiments only under a steady wind.

Quantitative field measurements of prescribed fire emissions impacting in typically far-removed receptor areas are also difficult to carry out due to frequent concurrent impacts from certain other very similar vegetation sources, such as field burning, wildfires, backyard burning, and home heating with wood. Characterization of the prescribed burning aerosol is a continuing and difficult task. Discovery of a reliable "signature" (i.e., identifying) compound would change this situation, but, until one is found, it has been necessary to correlate measured air quality monitoring samples with upwind burning activity.

Two studies in the Willamette Valley, Oregon, have reported upon specialized methods employed to overcome the inherent sampling problem. One, using gravimetric mass, particle size and upwind activity methods shows the relative prescribed burning impact upon ambient particulate matter levels to be greatest in rural areas (due to absences of impacts from other sources); to be small on a seasonal or annual basis when compared with geological impacts (i.e., from soil); but to be substantial for a few hours at a time (41). The other study utilized chemical mass balance, carbon-14 analysis, and upwind activity methods, and showed that all vegetation-burning sources together contribute the second largest total suspended particulate matter (TSP) impact (geologic sources being first). This study pointed to one sampling day when upwind activity indicated about half of the TSP carbon to be biogenic in origin, and primarily due to a slash fire. Fine particulate matter on this same day was largely attributed to the

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(40) Ward, D. E., R. M. Nelson, Jr., and D. F. Adams. Forest Fire Smoke Plume Documentation. Paper No. 79-6.3, Presented at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, June 24-29, 1979.

(41) Lyons, C. E., et al. Relating Particulate Matter Sources and Impacts in the Willamette Valley during Field and Slash Burning. Paper No. 79-46.3, Presented at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, June 24-29, 1979.

slash burning source, but again, only through the usually less certain method of determining what upwind activity had taken place. Home heating with wood was described as the most significant source of concern in the area (42).

Studies conducted in the laboratory have the advantage that both the quantity of fuel burned and the amount of pollutants produced can be monitored more accurately than in the field. Testing apparatus has been described in the literature (36, 43, 44) and generally consists of a platform on scales to hold the material to be burned. A large cone over the platform collects combustion products and funnels them to an exhaust stack where samples are withdrawn for analysis. To simulate backing fires and heading fires, the platform may be tilted at various angles. Particulate matter samples are collected isokinetically on glass fiber filters; carbon monoxide (CO) and total hydrocarbons (THC) are measured by continuous on-line analysis (nondispersive infrared for CO and flame ionization detection for THC). Grab samples are also taken for analysis of individual hydrocarbon (i.e., organic) species by gas chromatography and other methods. The stack gas flow rate is monitored so that emission data, flow rate data, and fuel consumption data can be combined to yield emission factors (grams of emissions produced per kilogram of fuel burned, dry weight basis).

Sampling and analysis procedures employed in laboratory studies are generally proven, reliable methods, and can be expected to yield good data. Analytical techniques for compounds classed as polycyclic organic material (POM) are, however, very complex and still subject to some debate. Three reported studies illustrate this point. One is a limited experimental series widely cited in projections of certain POM compounds for the prescribed fire source (often without the author's caution as to the limited number of samples). In this case, results reported were restricted to the anthracene-to-coronene fraction, included in the so called particulate polycyclic organic matter, intentionally avoiding dispute due to possible errors from high vapor pressures of

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(42) Cooper, J. A., J. G. Watson, and J. J. Huntzicker. Summary of the Portland Aerosol Characterization Study (PACS). Paper No. 79-24.4, Presented at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, June 24-29, 1979.

(43) Darley, E. F., F. R. Burleson, E. H. Mateer, J. T. Middleton, and V. P. Osterli. Contribution of Burning of Agricultural Wastes to Photochemical Air Pollution. Journal of the Air Pollution Control Association, 16(12):685-690, 1966.

(44) Gerstle, R. W., and D. A. Kemnitz. Atmospheric Emissions from Open Burning. Journal of the Air Pollution Control Association, 17(5):324-327, 1967.

such POM compounds as those of the naphthalenes (45, 46). Another study reports that the appreciable vapor pressures of a number of POM compounds at ambient temperature can cause filter samples to fail to include a significant portion of total material (47). In the third example, a recent study employed cold trap filters and reports the loss of benzo(a)pyrene from high volume-collected glass fiber filters to be less than 0.008 ng/m^3 (48). The procedure presently recommended by the EPA for sampling of POM's is with a fiber filter followed by a solid porous polymer sorbent trap (49).

The principal difficulty with laboratory studies lies in extrapolating the data to field conditions that differ, almost inevitably, from those in the laboratory. The present state of knowledge offers little in the way of correlative experiments that compare both lab and field emissions data for the same fuel type and firing technique. An exception is found in tests on southern pine understory which showed comparable results for both lab and field (32, 37). Additional work is needed to better establish the relationship between the two types of measurements.

EMISSIONS DATA

This subsection deals with results of published studies of emissions data in detail. In the next subsection, these data are

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(45) McMahon, C. K., and S. N. Tsoukalas. Polynuclear Aromatic Hydrocarbons in Forest Fire Smoke. Presented at the Second International Symposium on Polynuclear Aromatic Hydrocarbons, Columbus, Ohio, September 28-30, 1977. 21 pp.

(46) McMahon, C. K. Personal communication. U.S. Department of Agriculture, Forest Service, Macon, Georgia, March 29, 1979.

(47) Pupp, C., R. C. Lao, J. J. Murray, and R. F. Pottie. Equilibrium Vapour Concentrations of Some Polycyclic Aromatic Hydrocarbons, As_4O_6 and SeO_2 and the Collection Efficiencies of these Air Pollutants. Atmospheric Environment, 8:915-925, 1974.

(48) Miguel, A. H., and S. K. Friedlander. Distribution of BaP and Coronene...Submicron Range. Atmospheric Environment, 12(12):2407-2413, 1978.

(49) Lentzen, D. E., D. E. Wagoner, E. D. Estes, and W. F. Gutknecht. IERL-RTP Procedures Manual: Level 1 Environmental Assessment (Second Edition). EPA-600/7-78-201, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, October 1978. 279 pp.

summarized and an analyses of central tendencies is made by way of arriving at estimates of regional and national total annual criteria pollutant emissions production. The last subsection covers emission factors for local use.

Emissions data are commonly reported in terms of emission factors, i.e., the quantity of material emitted per unit of fuel burned. Available data for emissions of criteria pollutants from prescribed burning are compiled in Table 7 according to fuel type and test conditions (9, 30, 32, 37, 43, 50-54). An examination of Table 7 shows that most data are derived from laboratory tests. Also, comparatively few of the many possible prescribed burning conditions have been sampled. The wide spread in the data is indicative of how greatly emissions vary with fuel type and combustion conditions.

Some of the data for grassland in Table 7 resulted from studies of agricultural open burning rather than prescribed burning. It is beleived these best-available data may be cautiously used due to some similarities in fuels. At the same time, it must be recognized that agricultural fuels are usually many-fold more homogeneous in species composition, texture, and arrangement than are the similar fuels burned with prescribed fire.

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(50) Sandberg, D. V. Measurements of Particulate Emissions from Forest Residues in Open Burning Experiments. Ph.D. Thesis, College of Forest Resources, University of Washington, 1974.

(51) Ryan, P. W. Quantity and Quality of Smoke Produced by Southern Fuels in Prescribed Burning Operations. In: Proceedings of the National Conference on Fire and Forest Meteorology, American Meteorological Society and Society of American Foresters, Lake Tahoe, California, April 2-4, 1974.

(52) Benner, W. H., P. Urone, C. K. McMahon, and P. W. Ryan. Photochemical Potential of Forest Fire Smoke. Presented at the 70th Annual Meeting of the Air Pollution Control Association, Toronto, Ontario, Canada, June 20-24, 1977. 15 pp.

(53) Boubel, R. W., E. F. Darley, and E. A. Schuck. Emissions from Burning Grass and Straw. Journal of the Air Pollution Control Association, 19(7):497-500, 1969.

(54) Sandberg, D. V., S. G. Pickford, and E. F. Darley. Emissions from Slash Burning and the Influence of Flame Retardant Chemicals. Journal of the Air Pollution Control Association, 25(3):278-281, 1975.

TABLE 7. EMISSION FACTORS FOR PRESCRIBED FIRES

Fuel category	Fuel type	Test site	Type fire	Other test conditions	Emission factors, g/kg: Particulate matter	Hydrocarbons	CO	NO_x	Comments	Reference
I. BROADCAST ARRANGEMENT										
A. Understory	live understory (southern)	lab	--		12-48[a]					36
	live understory (southern)	field	backfire		7.5-15[a]					36
	pine needle litter (southern)	lab	backfire		8.5-14[a]					36
	pine needle litter (southern)	field	backfire		22-28[a]					36
	pine needle litter (southern)	lab	headfire		20-79[a]					31,36
	pine needle litter (southern)	lab	headfire	flaming combustion phase	7-25[a]					36
	pine needle litter (southern)	lab	headfire	smoldering combustion phase	32-90[a]					36
	slash pine needle litter	lab	backfire	50% slope; 18%-27% moisture content	3-14					29
	slash pine needle litter	lab	headfire	50% slope; 18%-27% moisture content						29
				a. average for total run	11-62					
				b. flaming phase	7-20					
				c. smoldering phase	32-90					
	pine needles (southern)	lab	a small (2 g) sample was ignited on a platform	14% moisture content		8.7 ± 3	68 ± 28	4.3 ± 1.0	Averages and standard deviation for best four runs. Data for all 16 runs are: Hydrocarbons, 9.25±3 g/kg; CO, 78±22 g/kg; and NO_x, 4.7±1.4 g/kg. Data for NO and NO_2 were also given; NO, 3.2±1.0 g/kg; NO_2, 1.6± 0.6 g/kg (data for 16 runs).	51
B. Brushfield	native brush San Joaquin Valley, California	lab	25# burned on flat platform	a. dry brush		2.4 ± 1.2[e]	35 ± 4		Mixtures of 11 species of brush were tested including such types as chamise, sagebrush, and manzanita. Other test data for fruit prunings yielded similar results.	42
				b. mixture of dry and		7.6 ± 2.2[e]	40 ± 3			
				c. green brush		13.7 ± 4.4[e]	67 ± 20			
	native brush San Francisco Bay Area, California, 1965	lab	25# burned on flat platform	moisture content of 5% ± 1%		2.4 ± 1.0[e]	32 ± 15			
	native brush San Francisco Bay Area, California, 1966	lab	25# burned on flat platform	moisture content of 13% ± 7%		2.2 ± 1.1[e]	28 ± 10			

(continued)

TABLE 7 (continued)

Fuel category	Fuel type	Test site	Type fire	Other test conditions	Emission factors, g/kg: Particulate matter	Hydrocarbons	CO	NO_x	Comments	Reference
C. Grassland	barley straw[d]	lab	25# burned on flat platform			7.2 ± 1.8[e]	42 ± 12			42
	rice straw[d]	lab	25# burned on flat platform			4.6 ± 1.2[e]	36 ± 8			
	six types of grass	lab	25# burned on flat platform	moisture content ranged from 5% to 15%	5.2 to 8.2	3.5 to 9[e]	42 to 74			52
	six types of grass	lab	25# burned on flat platform	moisture content ranged from 20% to 71%	4.5 to 13.0	2 to 9.5[a]	20 to 56			
D. Logging debris	logging residue (western)	lab				3 to 12				49
	logging residue (western)	field				14 to 54				49
	logging residue (eastern)	lab				--				31
	Ponderosa pine logging slash	lab[f]	30# burned on flat platform	a. untreated	6 ± 1	5.5 ± 1	98 ± 9		Moisture contents of needles were 4%-11%; of twigs, 3%-8%; of branches over 2 inches in diameter, 3%-14%. Relative humidity varied from 41% to 80%, temperature from 70°F to 90°F.	53
				b. treated with di-ammonium phosphate (DAP) at 3 gal/100 ft^2	12 ± 1.5	7.5 ± 2	116 ± 14			
				c. treated with DAP at 6 gal/100 ft^2	15 ± 1	9 ± 1	136 ± 12			
				d. treated with DAP at 12 gal/100 ft^2	18 ± 0.5	11 ± 1.5	133 ± 20			
II. PILED OR WINDROWED ARRANGEMENT										
A. Brushfields	no data									
B. Logging debris	no data									
C. Other	leaf piles from 15 species	lab	6# in a conical pile	dry leaves	4.7 to 38	1.3 to 32	26 to 95		Moisture content ranged from 6.4% to 26.6%. Windrows were occasionally ignited instead of piles.	42
	leaf pile of silver maple	lab	6# in a conical pile	mixture of dry and green leaves	82	23	73		Average moisture content was 24.1%; 19.1% for dry leaves and 41.9% for green leaves.	42

[a] Only particles less than 10 micron in diameter.

[b] Cited in Reference 31 from Reference 50.

[c] Basically same data as in Reference 36.

[d] Data are expected to be similar to those from grasslands.

[e] Reported as total carbon.

[f] Emission factors for this series of tests are reported in terms g pollutant/kg fuel actually consumed.

Emissions data from the residential combustion of wood are given for comparison in Table 8 (33-36, 55-57). It can be seen that both sets of data are in general agreement. Emissions from residential wood combustion may be expected to resemble emissions from wood and brush that is windrowed or piled for burning in the field. However, caution is warranted due to the high variability encountered, even in the contained environment of a stove or fireplace, where fuels are again more homogeneous than in open burning of piles and windrows. (Note, for example, the range of 0.7 to 26 for particulate matter in Table 8.)

Sulfur Oxides

Little data have been reported on emissions of sulfur oxides from prescribed fires, and they are considered a negligible emission for the prescribed fire source. In a recent study, the plumes from five prescribed fires were sampled from an airplane, and no significant gaseous sulfur was found (38). A material balance based on the sulfur content of vegetation (<0.2%) indicates that emission factors must be less than 4 g/kg. Data for coal combustion show that most of the sulfur in coal is released during the combustion process (58). Recent work with burning of wood bark (59) suggests a low conversion rate (approximately 5%) of bark sulfur to SO_2, with the balance accounted for in the ash combustion products. Another study on residential wood combustion showed that most of the fuel sulfur was released as SO_2 (56).

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(55) Source Testing for Fireplaces, Stoves, and Restaurant Grills in Vail, Colorado. (Draft) PEDCo Environmental, Inc., Contract 68-01-1999, U.S. Environmental Protection Agency, Region VIII, Denver, Colorado, December 1977. 26 pp.

(56) DeAngelis, D. G., and D. S. Ruffin. Source Assessment: Wood-Fired Residential Combustion Field Tests. Draft document in preparation by Monsanto Research Corporation, Contract 68-02-1874, for U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

(57) Butcher, S. S., and E. M. Sorenson. A Study of Wood Stove Particulate Emissions. Journal of the Air Pollution Control Association, 29(7):724-728, 1979.

(58) Compilation of Air Pollutant Emission Factors. Publication AP-42-A, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, February 1976. 216 pp.

(59) Oglesby, H. S., and R. O. Blosser. Information on the Sulfur Content of Bark and Its Contributions to SO_2 Emissions When Burned as Fuel. Paper 79-6.2, Presented at the 72nd Annual Meeting of the Air Pollution Control Association, Cincinnati, Ohio, June 24-29, 1979.

TABLE 8. EMISSION FACTORS FROM RESIDENTIAL WOOD COMBUSTION

Test unit	Emission factor, g/kg				Reference
	Particulate matter	Hydrocarbons	CO	NO_x	
Residential fireplaces (4 woods)	5.9 to 15.3 (10)[a]	2 to 3 (2.5)	43 to 87 (64)		32
Residential fireplaces	5.2 to 24 (11.4)	2.7 to 41.4 (20.6)	12.9 to 219 (65)	0.8 to 7.8 (2.1)	33
Wood stoves	0.7 to 25 (3.4)				34
Residential fireplace (4 woods)	15 to 26 (20)	10 to 390 (120)	28 to 140 (94)		54
Residential fireplace (4 woods)	8 to 12 (8.9)		15 to 30 (22)	1.4 to 2.4 (1.9)	55
Wood stoves (2 stoves, 4 woods)	5 to 18 (9.2)		91 to 370 (177)	0.2 to 0.8 (0.5)	55
Wood stoves (2 stoves, 2 woods)	1.3 to 24.4 (9.2)				56

[a]Values in parentheses are average emission factors for all measurements.

Nitrogen Oxides

In addition to the data in Table 7, data have been reported on NO_x emissions from the burning of landscape refuse in a laboratory study (44). Emission factors ranged from 0.25 g/kg to 2 g/kg. Another laboratory study reported only the NO_x concentration at the temperature peak during the combustion of various grass species (53). The concentration varied from 21 ppm to 72 ppm for dry grasses (20% to 71% moisture), showing that hotter fires produce higher NO_x levels. On the basis of these limited data, it is impossible to determine what fraction of NO_x emissions arise from fuel nitrogen and what fraction from atmospheric nitrogen. Progress toward this end has been made in a study utilizing a thermogravimetric system and a chemiluminescence nitrogen oxide analyzer to characterize production of nitrogen oxides from fuel-bound nitrogen. Fuel nitrogen is reported from that study to be an important source of NO_x for low temperature fires (<1,000°C), but results were not expected to hold for high intensity fires since thermal NO would be expected to dominate (60). It is currently impossible to predict how NO_x emissions will vary under different field conditions, pointing to the need for further experimentation.

Carbon Monoxide

Reported emission factors for carbon monoxide generally range from 20 g/kg to 100 g/kg, with the higher values associated with poorer combustion conditions such as green vegetation or higher moisture content material. Logging slash treated with the fire retardant chemical diammonium phosphate yielded CO emission factors in excess of 100 g/kg, presumably because the fire retardant caused a longer period of smoldering (54).

Emission factors for CO have all been derived from laboratory studies. Field studies have only measured CO concentrations

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(60) Clements, H. B., and C. K. McMahon. Nitrogen Oxides from Burning Forest Fuels Examined by Thermogravimetry and Evolved Gas Analysis. Manuscript at press, copy on file, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, 1979. 19 pp.

near the fire zone (61, 62), and found that they decrease rapidly with distance away from the fire. Further field studies are needed to relate CO concentrations to the mass of fuel actually consumed in a fire.

Hydrocarbons

Hydrocarbon emission factors for prescribed fires have been found to vary from 2 g/kg to 32 g/kg in laboratory tests. Combustion of green vegetation tended to yield higher emission factors, although the highest values reported were for dry leaves. Only one set of emission factors based on field studies was reported, 14 g/kg to 54 g/kg (50). Considering the extrapolations involved in calculating emission factors from field measurements, both lab and field data can be considered to be in good agreement.

A number of studies have characterized the hydrocarbons (i.e., organic compounds) emitted from prescribed fires (30, 43, 53, 54), and found a great number of species as illustrated in Figure 5 (30). The individual compounds observed, as well as the relative amount of different classes of compounds such as alkanes or olefins, are strongly influenced by the type of fuel and combustion conditions. In general, it has been found that the compounds present in the highest concentrations are the low-molecular weight hydrocarbons; methane, ethane, ethylene, propylene and acetylene (54). Under good combustion conditions (i.e., no smoldering), saturated and unsaturated hydrocarbons (alkanes, alkenes, and alkynes) make up about 50% of total hydrocarbon emissions (43, 53, 54).

The remaining carbonaceous material is composed of oxygenated species such as aldehydes, ketones, and organic acids. During poor combustion conditions, the relative percent of simple alkanes, olefins, and alkynes decreases and the proportion of other types of organic species increases (54). Additional studies are needed to correlate hydrocarbon emissions with combustion conditions and to characterize the organic species emitted, especially the oxygenated compounds.

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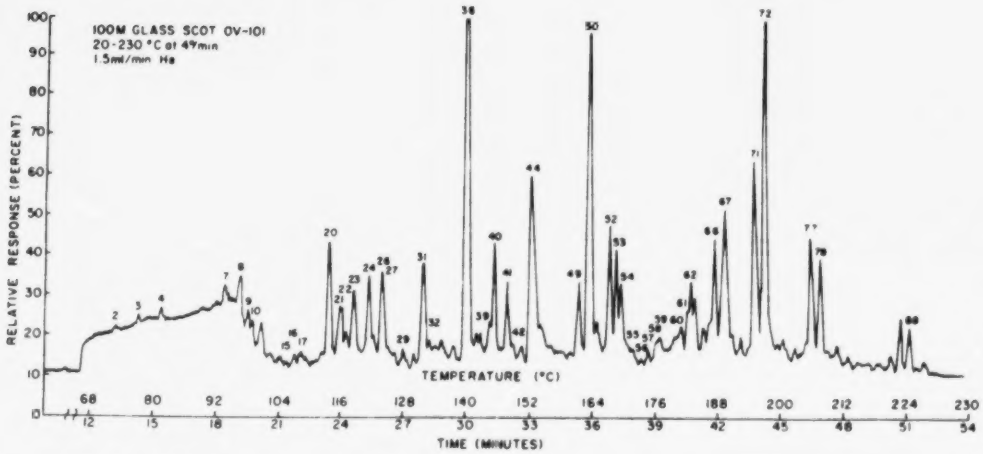
(61) Countryman, C. M. Mass Fires and Fire Behavior. Pacific Southwest Forest and Range Experiment Station Resource Paper PSW-19, U.S. Department of Agriculture, Forest Service, Berkeley, California, 1964.

(62) Fritschen, L., H. Bovee, K. Buettner, R. Charlson, L. Monteith, S. G. Pickford, J. J. Murphy, and E. F. Darley. Slash Fire Atmospheric Pollution. Forest Service Research Paper PNW-97 (PB 192 342), U.S. Department of Agriculture, Portland, Oregon, 1970. 42 pp.



PEAK	COMPOUND
2	isopentane
2B	1-pentene
2C	furan
3	n-pentane
3A	isoprene
3B	acetone
4A	isopropanol
4B	cyclopentadiene
7	diacetyl
8	1-hexene
8A	methyl vinyl ketone
9	2-methylfuran
10	n-hexane
15	2,4-hexadiene
16	1,3,5-hexatriene
17	3-methylbutanal
20	benzene
21	cyclohexane
22	4-methylpentene
23	2,4-dimethylpentane
24	1-trans-2-dimethyl-cyclopentane

PEAK	COMPOUND
24A	sorbaldehyde (tent.)
26	2,5-dimethylfuran
26A	n-heptene
27	cis-2-heptene
29	2-vinylfuran
31	2,3-dimethyl-2-pentane
32	2,4-dimethylhexane
36	toluene
39	1-octene
40	2,3-dimethylhexa-1,4-diene
41	n-octane
42	2,3,5-trimethylfuran
44	furfural
49	ethyl benzene
50	p-xylene
50A	2-propionylfuran (tent.)
52	styrene
53	o-xylene

PEAK	COMPOUND
54	n-nonane
54A	2-isopropylfuran
55	anisole
56	2-methyl-5-isopropenylfuran
57	cumene
58	n-decane
59	camphene (tent.)
60	n-propylbenzene
61	m-ethyltoluene
62	p-ethyltoluene
66	1-decene
67	benzofuran
71	m-diethylbenzene
72	limonene
77	p-α-dimethylstyrene
78	n-undecane
88	n-dodecane

Figure 5. Chromatogram of organic (C_4 to C_{12}) vapors in loblolly pine smoke. Each peak represents a separate compound (30).

One class of hydrocarbons that has received special attention is the polycyclic organic materials, or POM's. A number of these compounds (e.g., most widely referenced is benzo(a)pyrene) are known to be carcinogenic, and they are formed during most carbonaceous fuel combustion processes. Data on POM emissions from prescribed fires are sparse, and in fact there has been only one study (45) performed to measure POM emissions from prescribed fires, as that term is used in this report (i.e., in wildland management). This investigation simulated backing fires and heading fires using slash pine needle litter as the fuel, at three different fuel loadings. Emissions were channeled through a large stack where particulate matter samples were collected isokinetically on a glass fiber filter in a modified high volume sampler. Filters were extracted and the extract was analyzed for POM's by gas chromatography-mass spectrometry. Test results are shown in Tables 9, 10 and 11. Table 9 gives a breakdown of emissions from heading fires into the active burning (or flaming) phase and the smoldering phase.

As mentioned earlier in the discussion of measurement techniques, the data in Tables 9, 10 and 11 must be interpreted with caution. The limited amount of data also argues against coming to any definite conclusion, but there is an indication that POM emissions are higher under smoldering conditions than under flaming combustion. More surprising is the finding that the highest POM emissions occurred in a lightly loaded backing fire, while at the same time particulate emissions were higher for heading fires. Further studies are needed to explore this phenomenon before any definite conclusions are drawn.

Particulate Matter

Currently under one standard as total suspended particulate matter (TSP), this emission from prescribed fires has been studied much more extensively than gaseous emissions because it visibly affects air quality. TSP emission factors presented in Table 7 range from 2.5 g/kg to 90 g/kg, depending on fuel and combustion conditions. Of the two fire types, backing fires have generally lower emission factors than heading fires. This is believed to be mainly due to the differences in combustion efficiency. Combustion efficiency of smoldering fires, and of heading fires which leave large smoldering areas behind the flaming front, is less than for backing fires. TSP data from limited field experiments are in general agreement with lab studies.

A number of investigators have provided characterizations of the chemical and physical properties of particulate matter emissions. Unlike many other combustion sources where particles consist of inorganic ash, the particulate matter emissions from prescribed fires are primarily organic in nature. This is commonly measured by solvent extraction with benzene, with the benzene soluble organic (BSO) fraction ranging from 40 percent to 75 percent (30).

TABLE 9. POM EMISSION FACTORS FROM BURNING PINE NEEDLES BY FIRE TYPE, µg/kg OF FUEL BURNED; DRY WEIGHT BASIS[a] (45)

	Type fire and fuel loading											
	Backing fires			Heading fires			Heading fires by phase					
							Flaming	Smoldering	Flaming	Smoldering	Flaming	Smoldering
	0.5 kg/m²	1.5 kg/m²	2.4 kg/m²	0.5 kg/m²	1.5 kg/m²	2.4 kg/m²	0.5 kg/m²		1.5 kg/m²		2.4 kg/m²	
Anthracene/phenanthrene	12,181	2,189	584	2,525	5,542	6,768	1,621	7,049	865	9,046	2,351	8,791
Methyl anthracene	9,400	1,147	449	1,057	4,965	7,611	539	3,872	667	8,193	1,909	11,447
Fluoranthene	14,563	2,140	687	733	974	1,051	445	2,317	244	1,516	622	1,331
Pyrene	20,407	3,102	1,084	1,121	979	1,133	750	3,078	342	1,454	888	1,291
Methyl pyrene/fluoranthene	18,580	2,466	1,229	730	1,648	2,453	455	2,383	494	2,501	1,036	3,396
Benzo(c)phenanthrene	8,845	1,808	468	244	142	175	228	397	77	189	179	173
Chrysene/benz(a)anthracene	28,724	5,228	2,033	581	543	836	472	1,324	230	769	628	980
Methylchrysene	17,753	1,891	877	282	1,287	1,559	263	497	343	1,989	466	2,290
Benzofluoranthenes	12,835	1,216	818	164	129	241	178	199	69	174	90	347
Benzo(a)pyrene	3,454	555	238	40	97	33	100	17	55	36	140	
Benzo(e)pyrene	5,836	1,172	680	61	78	152	56	133	45	102	82	203
Perylene	2,128	198	134	33	24	46	38	33	14	32	27	61
Methylbenzopyrenes	6,582	963	384	65	198	665	19	397	52	304	75	1,069
Ideno(1,2,3-cd)pyrene	4,282	655	169	--	--	--	--	--	--	--	--	--
Benzo(ghi)perylene	6,181	1,009	419	--	--	--	--	--	--	--	--	--
TOTAL PPOM[b]	171,750	25,735	10,249	7,632	16,549	22,787	5,097	21,779	3,456	26,324	8,389	31,519
Total suspended particulate matter (TSP)	10 g/kg	4.5 g/kg	2.5 g/kg	10 g/kg	36 g/kg	59 g/kg	6.5 g/kg	28 g/kg	5.5 g/kg	82 g/kg	16 g/kg	111 g/kg
Benzene soluble organics	55 percent	50 percent	45 percent	44 percent	73 percent	75 percent	39 percent	48 percent	54 percent	76 percent	69 percent	76 percent

[a] Moisture content for all fires ranged between 18 to 27 percent

[b] Particulate polycyclic organic material

TABLE 10. POM EMISSION FACTORS FROM BURNING PINE NEEDLES BY FIRE TYPE, µg/kg OF FUEL BURNED; DRY WEIGHT BASIS[a] (45)

	Type fire and fuel loading											
	Backing fires			Heading fires			Heading fire by phase					
							Flaming	Smoldering	Flaming	Smoldering	Flaming	Smoldering
	0.5 kg/m²	1.5 kg/m²	2.4 kg/m²	0.5 kg/m²	1.5 kg/m²	2.4 kg/m²	0.5 kg/m²		1.5 kg/m²		2.4 kg/m²	
Anthracene/phenanthrene	12,181	2,189	584	2,525	5,542	6,768	1,621	7,049	865	9,046	2,351	8,791
Methyl anthracene	9,400	1,147	449	1,057	4,965	7,611	539	3,872	667	8,193	1,909	11,447
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Pyrene	20,407	3,102	1,084	1,121	979	1,133	750	3,078	342	1,454	888	1,291
Methyl pyrene/fluoranthene	18,580	2,466	1,229	730	1,648	2,453	455	2,383	494	2,501	1,036	3,396
Benzo(c)phenanthrene	8,845	1,808	468	244	142	175	228	397	77	189	179	173
Chrysene/benz(a)anthracene	28,724	5,228	2,033	581	543	836	472	1,324	230	769	628	980
Methylchrysene	17,753	1,891	877	282	1,287	1,559	263	497	343	1,989	466	2,290
Benzofluoranthenes	12,835	1,216	818	164	129	241	178	199	69	174	90	347
Benzo(a)pyrene	3,454	555	238	38	40	98	33	100	17	55	36	140
Benzo(e)pyrene	5,836	1,172	680	61	78	152	56	133	45	102	82	203
Perylene	2,128	198	134	33	24	46	38	33	14	32	27	61
Methylbenzopyrenes	6,582	963	384	65	198	665	19	397	52	304	75	1,069
Ideno(1,2,3-cd)pyrene	4,282	655	169	--	--	--	--	--	--	--	--	--
Benzo(ghi)perylene	6,181	1,009	419	--	--	--	--	--	--	--	--	--
PPOM[b]	171,750	25,735	10,249	7,632	16,549	22,787	5,097	21,779	3,456	26,324	8,389	31,519
Total suspended particulate matter (TSP)	10 g/kg	4.5 g/kg	2.5 g/kg	10 g/kg	36 g/kg	59 g/kg	6.5 g/kg	28 g/kg	5.5 g/kg	82 g/kg	16 g/kg	111 g/kg
Benzene soluble organics	55 percent	50 percent	45 percent	44 percent	73 percent	75 percent	39 percent	48 percent	54 percent	76 percent	69 percent	76 percent

[a] Moisture content for all fires ranged between 18 to 27 percent

[b] Particulate polycyclic organic material

TABLE 11. PPOM CONTENT OF TOTAL SUSPENDED PARTICULATE MATTER (TSP) FROM BURNING PINE NEEDLES, TSP (45)

Fire type	Fuel loading, kg/m² (lb/ft²)	Benzo(a)pyrene, µg/g	Total PPOM[a], µg/g
Backing	0.5 (0.1)	274	13,982
Backing	1.5 (0.3)	135	6,254
Backing	2.4 (0.5)	98	4,084
Heading	0.5 (0.1)	3	873
Heading	1.5 (0.3)	2	399
Heading	2.4 (0.5)	2	392

[a]Particulate polycyclic organic material

The organic character of particulate matter results from incomplete combustion in the fire zone. Organic species are volatilized by heat and, instead of being totally oxidized, are pyrolyzed or partially oxidized and escape to the air. Depending on their molecular weight, they may subsequently condense as liquid or solid particles in the submicron range. Some larger particles are also generated by entrainment of fuel fragments in hot combustion gases (30).

A number of studies have shown that most of the particulate matter released during prescribed fires is of submicron size. Tests on slash pine fires gave 70 percent of the particle mass below 0.4 μm and 95 percent below 1 μm. For palmetto-gallberry fires, the values are 51 percent below 0.4 μm and 91 percent below 1 μm (32). Studies in Australia (63) and England (64) reported that most wood smoke is in the neighborhood of 0.1 μm in diameter. In laboratory burning of Douglas fir logging slash, 82 percent of the particulate mass was found to be under 1 μm and 69 percent under 0.3 μm (65). Finally, a series of field experiments in the southeastern United States showed that the average particle diameter, on a number basis, was about 0.1 μm, independent of fuel type (30).

REGIONAL AND NATIONAL ESTIMATES OF THE ANNUAL PRODUCTION OF CRITERIA POLLUTANTS FROM PRESCRIBED FIRE

The preceding discussions have made it evident that there are wide variations in results of prescribed fire emissions studies. These variations are safely explained on the basis of natural variability alone. Because of this variability, and because of the many voids in knowledge regarding prescribed fire emissions, wide ranges of national estimates of annual emissions production from prescribed fire have resulted. In an examination of these several previous estimates, fuel consumed data and emission factors employed were seen to be causes for disagreement, and for suggesting a new national total suspended particulate matter (TSP) factor for prescribed fire (32). In suggesting a new national TSP factor of 25 g/kg, existing data in combination were weighed against the experience of the investigators with many

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(63) MacArthur, D. A. Particle Sizes in Bush Fire Smoke. Australian Forestry, 31:274-278, 1966.

(64) Foster, W. W. The Size of Wood Smoke Particles. International Journal of Air Pollution, 3:89-96, 1960.

(65) Sandberg, D. V., and R. E. Martin. Particle Sizes in Slash Fire Smoke. Pacific Northwest Forest and Range Experiment Station Research Paper PNW-199, U.S. Department of Agriculture, Portland, Oregon, 1975. 7 pp.

field and experimental fires. Another approach to coping with emission factor variability has been to express only the extremes, or "reasonable extremes" of reported factors. Two examples of this approach use a TSP emission factor range from 8 g/kg to 34 g/kg (66, 67), permitting the reviewer to recognize a real value lies somewhere within this four-fold interval.

While the available data do not lend themselves well to statistical inference, investigators needing to reach a single value are faced with the alternatives of: 1) arriving at either a judgmental approach (as in the 25 g/kg TSP example); 2) deriving their own averages from results of published studies; and 3) averaging the extremes of ranges (which for the 8-34 g/kg TSP range example would yield an arithmetic mean of 21 g/kg).

In arriving at mean values from published emission factors, as in alternative 2), above, there are some obvious risks. Important among these are the risks that a subpopulation will be given undue weight as a result of more studies in one area, or conversely, that another subpopulation will not be adequately represented as a result of only few, or no, studies in the area by which it is bounded. Some exhaustive studies may report only a single factor which is the result of analysis of many data points, while other studies may report several factors which are each representative of only a few data points.

Despite these risks, as well as those which enter with all judgments, the approach used for this report has been to follow a combination of the above alternatives 1) and 2). The rationale of this approach is to afford a measure of central tendency within the data employed, and to express an average national factor with an upper and lower limit, using as a basis what appear to be the most representative published emission factors. As with all other such estimates, it is necessary to caution that the above risks have been taken, and that the derived emission factors employed for regional and national estimates are not intended for further local application. Factors for local application are discussed in the next subsection.

Emission factors from preceding Tables 7 and 8 have been employed in derivation of national factors with the following provisions.

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(66) Cook, J. D., J. H. Himel, and R. H. Moyer. Impact of Forestry Burning Upon Air Quality: A State-of-the-Knowledge Characterization in Washington and Oregon. EPA-910/9-78-052, U.S. Environmental Protection Agency, Region X, Seattle, Washington, October 1978. 270 pp.

(67) Sandberg, D. V., et al. Effects of Fire on Air. Forest Service General Technical Report WO-9, U.S. Department of Agriculture, Washington, D.C., 1978. 40 pp.

In the case of understory values for TSP from Table 7, those reported for only the smoldering combustion phase have been excluded since these do not represent the entire period of the fire, as in other reported values. Table 7 values for piled leaves were not used. Table 8 data for residential fireplaces are used in part as a representation of the Piled and Windrowed fuel category. Wood stove data are excluded due to the greater dissimilarity of this type of combustion to prescribed fire. No attempt has been made to arrive at emission factors for nitrogen oxides due to the current uncertainty regarding fuel-bound versus atmospheric contributions of nitrogen.

Sulfur dioxide has not been analyzed due to the negligible emissions of this compound found in studies of the prescribed fire source. The notable emission of several sulfurous compounds found in studies of fire in organic soils of marshy areas (such as the Florida Everglades) are associated with prescribed fire only as proper prescriptions call for conditions which will prevent ignition of the soil in these areas. A further relationship to be expected is that an important tradeoff may, thus, be attributed to prescribed fires used to prevent subsequent wildfires during seasons when the organic soils will burn.

Emission factor data for TSP, CO, and THC were examined for a central tendency by calculating the arithmetic means and standard deviations for each group of factors. Lower and upper limits of the means were determined to n-1 degrees of freedom at the 95 percent confidence level. For this type of data, it is believed an indicated error of less than a factor of two is reasonable. Results of analysis showing the calculated values of statistical terms and error comparisons are presented in Table 12. Not shown in the table, but also of interest to the question of suitability of the data, comparisons were made of the derived mean TSP emission factor to those TSP factors used as examples in the preceding discussion. These comparisons show that the 25 g/kg example, and that the arithmetic, geometric, and quadratic means of the 8-34 g/kg range example, all fall within less than a factor of two error for the derived Table 12 TSP arithmetic mean of 17 g/kg.

The derived national mean emission factors, as well as their upper and lower limits, from Table 12 were used with regional net fuel consumed data from Table 3 to obtain estimates of regional and national annual prescribed fire criteria pollutant emissions production. The national estimates were then used to adjust currently published (68) national all-sources totals. Estimates

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(68) Eimutis, E. C., R. P. Quill, and G. M. Rinaldi. Source Assessment: State by State Listing of Criteria Pollutant Emissions (1978 Update). EPA-600/2-78-004s, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, July 1978. 155 pp.

TABLE 12. RESULTS OF ANALYSIS OF NATIONAL CRITERIA POLLUTANT EMISSION FACTOR DATA FROM TABLES 7 AND 8

Criteria pollutant	Rounded emission factor statistics,[a] g/kg				Ranges of emission factors used from Tables 8 and 9	Error comparisons results	
	S_X	$\bar{X}_{L95}$	$\bar{X}$	$\bar{X}_{U95}$		$\frac{S_X}{\bar{X}}$	$\frac{\bar{X}_{U95}}{\bar{X}_{L95}}$
Total suspended particulate matter, TSP	18	12	17	23	2 - 79	1.02	1.98
Carbon monoxide, CO	43	42	56	69	12.9-21.9	.78	1.64
Total hydrocarbons, THC	12	5	9	12	1 - 54	1.30	2.36
Nitrogen oxides, NO_x	Not estimated (see text)						
Sulfur dioxide, SO_2	Negligible						

[a] Symbols used:

S_X = standard deviation of the sample.

$\bar{X}_{L95}$ = lower limit of the mean at 95% confidence level.

$\bar{X}$ = arithmetic mean.

$\bar{X}_{U95}$ = upper limit of the mean at 95% confidence level.

$\frac{S_X}{\bar{X}}$ = coefficient of variation.

of the relative national production of prescribed fire to production from all sources were then made as percentages. The cited publication includes fugitive dust from certain defined sources such as roads. The original reference should be consulted for more detailed definitions of sources if needed for further analyses. It should be noted that the national totals used from that publication required some further corrections before used, due to a few inconsistencies in state totals. Resulting estimates are presented in Table 13.

"SAFE-SIDED" EMISSION FACTORS FOR LOCAL USE

The derived average emission factors used for regional and national estimates in the preceding subsection should not be used for further localized estimates.

Only a portion of the important fuel types in the southern states have been covered by studies which have permitted some suggested TSP emission factors to be cautiously advanced for operational smoke management (9). Procedures are published with these for using the factors to make predictions of emissions at different combustion stages and moisture levels, as well as for determining appropriate emission rates. Current studies and proposals promise to offer improved and interim factors and procedures for additional fuels and firing techniques (25, 26).

For use in the meantime, an attempt is herein made to provide "safe-sided" emission factors. Prescribed burners may elect to use these instead of national average emission factors for want of any other values. This attempt draws upon the few available data points for each of several prescribed fire categories in preceding Tables 7 and 8. Of these categories, the largest samples are for backing fires in understory vegetation and litter and for piled and windrowed residues (n = 8). The smallest samples are for grass, understory heading fires, and broadcast timber harvesting residues (n=4, each). Because this is a very weak data base, a method has been devised by which users of prescribed fire may select their own "safe-sided" value from any array of values. Only the TSP data from preceding Tables 7 and 8 have been used in this approach, as a suggested starting point for downwind concentrations predictions.

While the arithmetic mean of a sample population is ordinarily the best single estimate of the overall population mean, the variations found in the limited number of samples available for this approach result in several extremely wide limits of the means. This implies that these calculated arithmetic mean values are not apt to be adequate in themselves for the purpose of maintaining local air quality to an acceptable level. The less frequently used quadratic mean, because it employs an average of the squares of all values in the sample distribution, is weighted toward the

TABLE 13. REGIONAL AND NATIONAL ESTIMATES OF ANNUAL CRITERIA POLLUTANT PRODUCTION FROM PRESCRIBED FIRE, INCLUDING COMPARISONS WITH NATIONAL PRODUCTION FROM ALL SOURCES[a,b,c]
(10^3 metric tons)

Estimate type	Estimate of annual fuel consumed (all categories), Tg	Total suspended particulate matter at 10 g/kg	at 17 g/kg	at 24 g/kg	Total hydrocarbons at 5 g/kg	at 9 g/kg	at 13 g/kg	Carbon monoxide at 40 g/kg	at 56 g/kg	at 72 g/kg
Regional										
Alaska	0.05	0.5	0.8	1.2	0.2	0.4	0.6	2.0	2.8	3.6
Eastern	0.05	0.5	0.8	1.2	0.2	0.4	0.6	2.0	2.8	3.6
Intermountain	0.76	7.6	12.9	18.2	3.8	6.8	9.9	30.4	42.6	54.7
Northern	8.90	89.0	151.3	213.6	44.5	80.1	115.7	356.0	498.4	640.8
Pacific N.W.	8.74	87.4	148.6	209.8	43.7	78.6	113.6	349.8	489.4	629.3
Pacific S.W.	2.89	28.9	49.1	69.4	14.4	26.0	37.6	115.6	161.8	208.1
Rocky Mtn.	0.61	6.1	10.4	14.6	3.1	5.5	7.9	24.4	34.2	43.9
Southern	12.50	125.0	212.5	300.0	62.5	112.5	162.5	500.0	700.0	900.0
Southwestern	2.09	20.9	35.5	50.2	10.5	18.8	27.2	83.6	117.0	150.5
National and Comparisons										
(1) Total of means (all regions)		365.9	621.9	878.2	182.9	329.1	475.6	1,463.6	2,049.0	2,634.5
(2) Comparative totals from 1978 Update Criteria Pollutants (68)										
(a) National total, prescribed fire source			377.8			98.2			740.4	
(b) National total, all sources			123,010.2			11,818.6			89,192.4	
(3) Adjusted national total, all sources (line 1 - line 2a + line 2b)			123,254.3			12,049.5			90,501.0	
(4) Percent prescribed fire, this study compared to adjusted national total, all sources (line 1 : line 3)			0.5			2.7			2.0	

[a] Derived national emission factors used in this table should not be applied locally; see Section 5 instead.

[b] Nitrogen oxide emissions not estimated (see text).

[c] Sulfur dioxide negligible.

high side. By itself, however, the quadratic mean gives no statement of confidence. By an examination of the trends of all the derived arithmetic means, quadratic means, and each of several upper limits of the means between categories, it is believed likely that a user can select a "safe-sided" value more representative of his local situation than by any other method currently available.

Figure 6 has been prepared in an attempt to provide for such a composite examination. In addition to comparisons within categories (vertical axis), the same statistic for the separate distributions in each of five prescribed fire categories may be compared between categories (horizontal axis). It is of interest to note that even with the limited data base available, the previously reported (32) approximate 3:1 ratio of TSP emissions between understory heading and backing fires holds for both the arithmetic and quadratic means of these two distributions. The principal utility of the semi-logarithmic plot (vertical axis) of this family of curves is, however, in the ways it may be used for "high-sided" estimates. These possible uses are illustrated by a series of examples which follow.

In the following series of conjectural examples of possible uses of Figure 6, each example is preceded by the same symbol which appears on the figure.

1. Because of an unusually large amount of fresh pine needles still readily available with the residues, and because of uncertainty about the effect of fuel moisture in the larger fuels, 50 mg/kg, the upper limit of the mean at the 99 percent confidence interval,[a] is selected for conservatism.

2. Noting a seeming departure of the arithmetic mean from the general shape of the family of curves, the apparently safer quadratic mean value of 19.5 mg/kg is selected for use.

3. A selection of this moderately "safe-sided" 15.9 mg/kg value might result from the belief that while the planned burn is fairly typical, fuel moisture is not adequately known.

4. For the values presented, a combination of heading and backing fires is assumed since neither is specified; since only heading fires will be used, a high, "safe-sided" 16.5 mg/kg value is selected.

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[a]Strictly, the confidence interval implies that for the population represented by the sample, the average is expected to fall between the upper and lower limits of the mean that percent of the time. In this example, the upper limit of the mean, $\bar{X}_{u_{99}}$, is read 50 mg/kg, and it is implied that the population average should not be greater more than one percent of the time.

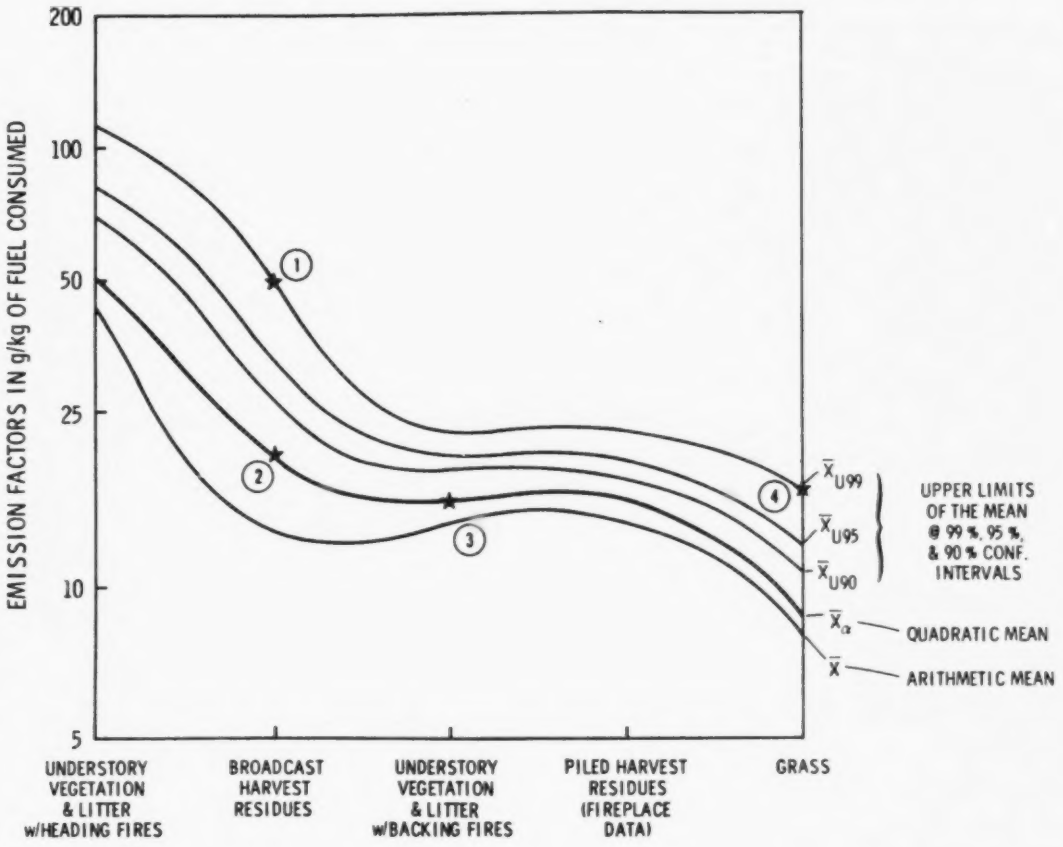

Figure 6. Family of curves showing Arithmetic Mean and several "Safe-sided" statistics for determining total suspended particulate matter emission factors for different categories of fuel and fire types. Starred numbers refer to examples of use in accompanying text.

SECTION 6

CONTROL TECHNOLOGY

INTRODUCTION

As applied to prescribed burning, the term control technology may be defined as either alternatives to burning in which prescribed fires are no longer used, or use of best-available control technology whereby emissions from prescribed fires are reduced, dispersed, and directed away from critical areas. Both approaches have certain advantages and disadvantages, and a careful evaluation is needed before choosing an optimum mix of control techniques for any given situation. In some cases (e.g., disease control, meeting natural ecosystem requirements, or habitat improvement), there may be no viable alternative to burning. Consequently, the objectives for use of prescribed fire must be well defined before a control technique is selected, and the benefits must be weighed against the costs in terms of environmental impact.

Within the land management community where prescribed fire is used, "smoke management" is regarded as the means by which control technology can be effected. This section will, thus, examine current and emerging smoke management technology for parallels to the control technology statements of the preceding paragraph. A recently advanced (69) definition of, and proposed methods for, smoke management serves to initiate this examination. The definition is:

> SMOKE MANAGEMENT: Procedures by which prescribed fire and its alternatives are appraised and by which conditions are specified for operating plans prepared to maintain air quality to acceptable levels in areas of importance.

Methods proposed for appraisals of prescribed fire call for determination of both net air quality impact and net benefit margins for prescribed fire and its alternatives. Methods for specifying conditions that limit air quality impacts call for development of

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(69) Paulson, N. Personal communication in reference to internal committee report NWAQ Team. U.S. Department of Agriculture, Forest Service, Washington, D.C., 1979.

an Operating Plan which is based upon the same fuels, atmospheric, and fire criteria found acceptable in appraising the air quality impact.

GENERAL CONSIDERATIONS

Factors that influence the application of control technology to prescribed fires include the existing ambient air quality, the air standards for the region, the contribution to ambient air pollutant concentrations by prescribed fires, and the impact of other sources, as well as national and local importance of the prescribed burning source. The seasonal nature of prescribed burning, the short duration of individual burns, the proximity of designated nonattainment areas, and public safety will all affect evolution of both voluntary and regulatory processes. This evolution will be discussed further in Section 7.

The following subsections describe available and emerging control technologies applicable to prescribed fire, relating these to smoke management and summarizing their major advantages and disadvantages. It is impossible to cite any one method as the best approach for all situations. To be successful, smoke management planning under the above definition provides for sorting of these many variables to arrive at locally appropriate control technology selections (69).

APPRAISALS OF PRESCRIBED FIRE

Appraisals in Terms of Effects on Air Quality

To make prescribed fire appraisals, emission factors are needed for local use. These should be specifically tied to local fuels and firing techniques. Field and laboratory measurements (described in Section 5) are very expensive, and will still result in wide ranges due to the highly variable natural relationships involved. Previously referenced interim methods proposed for emission and heat-release rate information (26) are deemed necessary while more broadly applicable predictive equations are developed and validated (25). Some "safe-sided" factors for TSP have been provided in Section 5 of this report (Figure 6). Where heat-release rates and emission factors are locally available (9), smoke management can now be effected with more certainty. But, air quality and land management personnel, and in some cases legislators, are faced with complex issues that are demanding air quality appraisals now. To not make the best possible appraisals means that risks must be taken and that promulgated regulations may be difficult to replace even when better control technology is brought to bear. Issues have had to be resolved under this uncertainty already. For example, open burning is now specifically prohibited in one state for materials which are deliberately

piled or bunched to prepare forest land for planting or seeding (70).

Short-term peak concentrations are believed to be the main concern for short-lived prescribed fires. For these fires, typical case examples have been provided to southern land managers where rate information is available and an operational adaptation of EPA-approved models has been made (9). One such southern case example is illustrated in Table 14. This approach has utility for appraisals where emissions production is of short duration (i.e., <3 or 4 hours).

In many areas of the country, air quality portions of prescribed fire appraisals can be made through uses of simple case examples like the one illustrated by Table 14. Another fairly simple example is found in a smoke management plan now under preparation; in the case study area covered, the greatest smoke management concern appears to be only to maintain adequate visibility for safe operations at an adjoining airstrip, and along traveled roads (71). In appraising the air quality effects of the burning program in this example, areas of local concern were delineated, and local authorities were requested to supply air quality criteria. Then, through one-time use of a relatively simple automated-data program known by the acronym PRESMOK (72), downwind TSP concentrations of planned burns were predicted. (PRESMOK is an adaptation of an EPA-recommended model validated for flat and rolling terrain.) By carefully specifying wind directions, and limiting the planned size of some areas to be burned, predicted concentrations were maintained within the preset criteria.

Not all parts of the country can be handled this simply. In some, "background" air pollution levels are already high from other sources, heavily populated areas are nearby, complex terrain and/or multiple fires are involved, and large amounts of fuel must be treated. In cases combining elements like these,

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(70) Virginia, Commonwealth of. Forest Management and Agricultural Practices (from Appendix D). In: Regulations Concerning Open Burning. Pamphlet, State Air Pollution Board, Richmond, Virginia. Undated. 8 pp.

(71) Johansen, R. W., and R. A. Phernetton. Managing Smoke from Prescription Burning on the Okefenokee National Wildlife Refuge. Manuscript in progress, draft on file, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, 1979. 15+ pp.

(72) Lavdas, L. G. PRESMOK, Operational Prescribed Fire Smoke Dispersion Computer Program. Documentation on file, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, 1978.

TABLE 14. ILLUSTRATION OF TYPICAL SHORT-TERM PEAK TSP CONCENTRATIONS DATA WITH UTILITY FOR AIR QUALITY-RELATED APPRAISALS OF PRESCRIBED FIRES OF SHORT DURATION (i.e., <3 or 4 HOURS). ADAPTED FROM TABLES IN REFERENCE 9

Type of fire	Pasquill stability class	Mixing height, km	Heat release rate, megacal/sec	Length of fired line or equiv., m	Transport windspeed, m/sec	Emission rate, mg/m-sec
Palmetto-gallberry: backing fire	C	1.5	37.632	800	8	168
Palmetto-gallberry: heading fire in 2-year-old rough	C	1.5	137.984	800	8	616

Particulate matter concentrations at various distances downwind, $\mu g/m^3$

Distance downwind, km	Backing fire	Heading fire in 2-year-old roughs
0.10	901	3,302
.13	730	2,675
.16	591	2,167
.20	479	1,756
.25	388	1,422
.32	314	1,152
.40	256	933
.50	206	756
.63	167	612
.79	135	496
1.00	110	402
1.30	90	325
1.60	72	261
2.00	57	206
2.50	45	157
3.20	37	116
4.00	31	83
5.00	25	59
6.30	19	43
7.90	14	32
10.00	10	25
13.00	7	20
16.00	5	15
20.00	3	10
25.00	2	8
32.00	2	7
40.00	1	6
50.00	1	5
63.00	1	4
79.00	1	3
100.00	1	3

differing levels of sophistication are needed. In the following discussion, examples are drawn from currently active research and development to illustrate how these needs are being met.

Quantitative determination of local air quality effects of prescribed fire is dependent upon TSP and other criteria pollutant background concentrations data for potential receptor areas. Also needed are climatologies of atmospheric dispersion parameters during the burning season. These data are generally available, but often lack desired localization in land management areas remote from monitoring and weather observation stations.

EPA designation of nonattainment areas has served to flag areas where violations of National Ambient Air Quality Standards have occurred or are expected. Though sometimes encompassing large areas which may not be of entirely the same air quality, nonattainment areas are useful to smoke management. These designations will serve to alert prescribed fire appriasers of the need to be especially careful in examining background levels of criteria pollutants in receptor areas designated nonattainment, and to select optimum diffusion parameters if smoke is to be vectored toward them.

A pilot test of supplying prescribed burners with information on nonattainment area locations and the bases for designations is now in progress using an experimental automated data processing program known by the acronym "SMKLCR" (73). With this program, the user merely enters the latitude and longitude of the location where burning is to be done, and the azimuth(s) of expected transport winds. He is then furnished with the approximate centerpoint location, the name, and the type(s) of designation for any EPA-designated nonattainment areas within 100 kilometers that may be impacted by smoke from the location of the burning. (More precisely, SMKLCR searches a file of nonattainment area effective radii for any within 100 kilometers of a fire's centerpoint location.)

A further use is made of this program by its automatic incorporation in operational smoke management procedures which are being made available for verifying the real-time effects of meteorologically scheduled burning, discussed in the following section. One of these is the program called "RXBURN" (74), an adaptation of a

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(73) Rodgers, S. L. SMKLCR. Computer Program Automatically Flagging Nonattainment Areas Toward which Prescribed Fire Smoke May be Advected. Documentation on file, Southeastern Forest Experiment Station, Asheville, North Carolina.

(74) Paul, J. T., J. M. Pierovich, L. G. Lavdas, and S. L. Rodgers. RXBURN Prescribed Burning/Smoke Management Decision Module Computer Program. Documentation on file, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina.

validated EPA-recommended model for flat and rolling terrain. RXBURN can also be used for prescribed fire appraisals in flat and rolling terrain by substituting climatological data in place of the automated observed and forecast data used in operational procedures on the day of burning.

In heavy fuels (which may burn for more than a day), it becomes necessary to incorporate "decay rate" adjustments to emission factors and heat release, and to allow for the times of constant emissions duration, for the time of end of convective lift, and for changing dispersion parameters with time.[a] An experimental program called "HRSMOK" (75) allows for making hourly adjustments to these variables and affords the approach by which adapted steady-state Gaussian dispersion models may be made usable for heavy fuels. PRESMOK and RXBURN, mentioned above for flat and rolling terrain, are now under examination for this further adaptation.

Meteorology and smoke dispersion in complex terrain are coming under increased attention, both as the HRSMOK experimental program will permit automated changes in emissions and heat-release inputs for this need, and as the EPA-recommended RAM (76, 77) and CDM (78, 79) models are proposed for adaptaion and validation

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[a]See also Section 3 for discussion of convective lift, constant emissions duration, and decay rates.

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(75) Lavdas, L. G. HRSMK Experimental Prescribed Fire Smoke Dispersion Computer Program. Documentation on file, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, 1978.

(76) Turner, D. B., and J. H. Novak. User's Guide for RAM, Volume I. EPA-600/8-78-016a, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1978. 60 pp.

(77) Turner, D. B., and J. H. Novak. User's Guide for Ram, Volume II. EPA-600/8-78-016b, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1978. 222 pp.

(78) Burse, A. D., and J. R. Zimmerman. User's Guide for the Climatological Dispersion Model. EPA-R4-73-024, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1973. 131 pp.

(79) Brubaker, K. L., P. Brown, and R. R. Cirillo. Addendum to User's Guide for Climatological Dispersion Model. EPA-450/3-77-015, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1977. 134 pp.

through new coefficients now under development (80). These models will also accommodate more than one fire in the same area and are similar in hour-by-hour accounting procedures used with the Gaussian steady-state equation they employ.

Yet another approach under examination for complex terrain and multiple fires would employ the most advanced technology by which temporal and spatial changes are reflected in grids, or in air parcels, to predict concentrations. With these methods, effects of specific topographic features may be represented as has been demonstrated for LIRAQ and other such models (81). A deterrent to their use, however, has been the very high cost of the computational requirements for the involved equations. Now it is suggested the power of the models warrants at least adaptations for those specific mountain airsheds where air quality is critical and lesser approaches do not yield satisfactory results. The approach under examination would overcome these costs by uing typical combinations of weather, fuels, and fire variables to create an area-specific "library" of expected results. The "library" is then automatically searched for comparability to actual situations (either on a climatological planning and appraised basis or possibly on a day-in-day-out operational basis), with resulting predictions made available at a fraction of the cost that would be otherwise incurred.

Appraisals in Terms of Alternatives to Burning

Alternatives to prescribed burning are being seriously pursued. General categories of alternatives include mechanical treatment, chemical treatment, improved utilization, and no treatment. The feasibility of each alternative varies with the type of application. For example, the use of acceptable herbicides to control understory growth for reduction of fire hazard might adversely affect wildlife habitat and would not be relevant at all to treatment of harvesting residues in the Northwest. Conversely, improved harvesting and utilization developed on the Pacific coast would not be applicable to wildlife habitat improvement in the South.

Relative advantages and disadvantages of different methods are difficult to compare because net benefits cannot always be measured on the same basis. The factor that is generally the least difficult to quantify is the direct economic cost (capital and operating), in terms of dollars per ton or dollars per acre of

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(80) Fosberg, M. A. Personal communication. U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Riverside, California, August 1979.

(81) Turner, D. B. Atmospheric Dispersion Modelling - A Critical Review. Journal of the Air Pollution Control Association, 29(5):502-519, 1979.

treatment. This type of information is available on several alternatives and shows, as expected, that prescribed burning is usually the least expensive form of land treatment (66). The alternative of no treatment obviously involves no direct treatment cost.

Unfortunately, the direct economic cost is only the tip of an iceberg. Site variability has a profound effect on operating costs, and the cost data are too limited and scattered to draw anything more than general conclusions. Even more important, it is impossible to quantify the indirect costs and benefits of different treatment alternatives. Some pertinent factors that cannot be fully quantified from data available today are (9, 66):

- The net value of fire hazard reduction (an indirect cost of no treatment)
- Net esthetic impact
- Net environmental impact of mechanical or chemical treatment
- Net air quality improvement as a result of no burning (allowance must here be made for contributions of emissions from wildfires that would result)
- Net silvicultural considerations (e.g., controlled disease; species optimization, optimum stocking)
- Net ecosystem response (affecting other net impacts)

In light of these considerations, the following descriptions of treatment alternatives do not offer quantitative effect information nor draw conclusions in terms of what method is best. Qualitative advantages and disadvantages are given, as well as the type of application each method may be suited for.

Mechanical Treatment--
Different types of mechanical treatment can be used to clear away brush and trees, to prepare land for planting, to break up slash into finer material, and to dispose of slash or brush by burial in gentle terrain. These techniques are not effective for control of understory species without damage to the overstory, for disease control, for reduction of fire hazard (except burial), or for wildlife habitat improvement; nor can they be used on steep slopes (9, 66). They are also energy demanding.

Brush and tree removal--Mechanical choppers and shredders can be used to clear away brush and trees for tree planting in open areas. Their cost of operation is high and limits their use to smaller areas such as openings in forest tracts. Moreover, the debris left behind may have to be disposed of to avoid a fire hazard (9, 66).

Site preparation and scarification--In addition to choppers and shredders, bulldozers or tractors may be used to clear land for planting. However, this kind of clearing has potential for soil compaction and increased erosion. Scarification, or clearing

away all vegetation to expose the soil, is used as an effective method of preparing firebreaks in fire-prone areas (9, 66), but is less applicable to the frequently preferred shaded fuel break.

Slash treatment--Slash can be reduced to finer material by various types of choppers and shredders. Although slash material is not eliminated, it may be easier to dispose of by other methods or through natural decay. If a fire hazard still exists, some type of prescribed burning may be needed (9, 66).

To reduce the cost of slash treatment and minimize land damage, yarding techniques are often employed to gather slash into one central location. Yarding is also used to gather slash for burning (66).

Burying--In flat terrain, burial is a method of very limited application for the disposal of logging slash. This method involves digging trenches to push the slash into and then covering the slash with dirt. Burial has the advantage that no flammable material is left on the surface as a fire hazard. It cannot be used in rocky soil and may leave barren soil exposed to erosion (66). Tree diseases, such as *Fomes annosus* and *Armellaria mellea*, are known to colonize buried harvesting residues, leading to losses of desirable timber (82).

Chemical Treatments--
Chemical treatments, such as the application of herbicides, have been used for specific purposes, e.g., seedbed preparation and brush control. The development of selective herbicides (compounds that are only toxic to certain species) has made this technique useful in more applications. Such treatments, however, can only be applied to live vegetation and do nothing to reduce fire hazard; indeed the risk of fire may actually increase as the dead vegetation dries. Recent suspension of the herbicide, 2,4,5-T has seriously limited this silvicultural treament alternative. Thus, chemical treatment is an alternative to prescribed fires in only certain situations (9, 66).

Improved Utilization--
Improved utilization is an attractive alternative to prescribed burning that encompasses both improved harvesting techniques that generate less slash and new end uses for material that is normally burned. Examples of improved harvesting methods that are being used or under development include (66):

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(82) Nelson, E. E., and G. M. Harvey. Diseases. In: Environmental Effects of Forest Residues Management in the Pacific Northwest, Compend. O. P. Cramer, ed. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, 1974. pp. S3-S5.

- Directional felling to reduce log breakage
- Prelogging or postlogging to recover small diameter timber
- Better handling techniques that will accept material normally discarded as slash
- Design of contractual agreements to encourage recovery of small size material

Progress is also being made in using the entire logged tree, thus eliminating any slash. In the South, merchantable pine trees are often utilized down to diameters of 55 mm to 100 mm (9). Rising demand (and prices) for wood fiber raw materials, and possible uses of forest residues (including tops, branches, foliage, bark, stumps, roots, small stems, and dead standing trees) as fuel and as a source of chemicals, all contribute toward progress in industrial use of the whole tree (83). A general guideline, however, is to minimize the loss of fine textured residues since these are a principal source of soil humus and many nutrients needed for forest growth (84).

Whole-tree chipping, a new technique of harvesting forest products for complete utilization, looks promising. Large, transportable chippers mounted on semitrailers accept whole trees and cut them into chips which can be blown into a truck and hauled to a pulp mill. No appreciable logging debris is left on areas logged in this manner (9).

When slash must be transported to a processing site, physical and economic limitations are imposed by material handling and transportation systems. Advances in these areas include preprocessing for optimum size grading of slash or for conversion of slash into chips or pellets, and new and modified hauling systems for nonstandard size logs or wood chips (66).

In order for improved utilization to be an acceptable alternative, there must be a market for timber-harvesting residues. At the present time, the two primary outlets for harvesting residues are in the pulp and paper industry and for boiler fuel. New pulp digestion processes can accept substantial amounts of material containing bark and leaves. Various forest industries can also use hogged slash as fuel for industrial boilers (9, 66), and

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(83) Quinney, D. N. Economics of Utilizing Residuals from Logging - Problems and Opportunities. American Institute of Chemical Engineers Symposium Series, 71(146):30-32, 1975.

(84) Miller, R. E., R. L. Williamson, and R. R. Silen. In: Environmental Effects of Forest Residues Management in the Pacific Northwest, Compend. O. P. Cramer, ed. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon, 1974. p. J11.

increased attention is being given to timber-harvesting and land-clearing residues as sources of energy. Energy balance (i.e., the amount of energy expended for collection, hauling, storage, and processing) must, however, be accounted for in assessing this alternative.

Improved utilization cannot replace prescribed burning in range management and in removal of understory growth and litter within the timber stands. In these cases, volumes are too low and scattered to justify the cost of harvesting the material, especially when the material has to be removed from among tree stems. There is currently no developed market for most of this material (9).

No Treatment--
Although the elimination of any form of treatment including prescribed burning poses no immediate adverse effects to the environment, it does not accomplish any of the benefits for which prescribed fires are used (see Section 3). Moreover, no treatment for extended periods of time can lead to increased risks of losses due to wildfire, to insect infestation, to losses of species diversity and site productivity, as well as to other undersirable effects. Thus, it cannot be considered a viable alternative in most situations (9, 66).

OPERATING PLANS FOR SMOKE MANAGEMENT

Operating plans for smoke management are in effect to different levels of sophistication in several states (85-89). Permit

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(85) Kilian, L. Designated SF-FM, Practices, Coordination of Prescribed Burning Activities. Unpublished memorandum with enclosures, North Carolina Division of Forest Resources, 1974. 14 pp. w/encl.

(86) Montana, State of. State of Montana Cooperative Smoke Management Plan. Unpublished agreement on file, State of Montana, Division of Forestry, Helena, Montana, 1978. 6 pp. + exhibits.

(87) Oregon, State of. Directive 1-1-3-410, Smoke Management Plan. Unpublished plan on file, Oregon State Board of Forestry, 1972. 14 pp.

(88) Oregon, State of. Directive 1-1-3-411, Operational Details for the Oregon Smoke Management Plan. Unpublished plan on file, Oregon State Board of Forestry, 1978. 20 pp.

(89) Washington, State of. Smoke Management Program. State of Washington, Department of Natural Resources, Olympia, Washington, 1975. 17 pp. + exhibits.

systems resulting in different levels of smoke management are also in effect (9, 90). In many states, blanket air quality regulations make avoidance of violation of the National Ambient Air Quality Standards incumbent upon all sources of emissions. In essence, a combination of voluntary and regulated control technology is being applied.

This combination may work well today where applied. Questions remain, however: how well will chosen control measures operate in the light of new interpretations of existing regulations, or of those yet to be promulgated; will they operate when the prescribed burning practice may be extended to new areas, or are requirements already too stringent in some areas? Unanswered questions like these, originating in a lack of data about the source and its emissions, tend to impede implementation of available technology. Complete dependence upon subjectivity in matters of this importance will beget indecision, advocacy, and even adversary situations.

The appraisals discussed in preceding sections demonstrate techniques for partial quantifications by which decision can be reached and delays minimized. A major impediment is lack of guidance, and/or of commitment to acceptance of those measures which might be implemented, on the part of air quality regulatory agencies.

Each of the following sketches of operating plan components is intended to summarize the available and emerging technology, giving relative levels of sophistication, in order to facilitate removal of these impediments. "Sophistication" relates only to application of the technology, and has no relation to cost or to difficulty of underlying research and development.

Specification of Fuels Characteristics

Fuel characteristics are obviously a prime factor affecting the magnitude of emissions from prescribed burning. Important parameters include fuel amount, fuel loading, fuel moisture content, and the physical arrangement of the fuel. Each of these items should be addressed as part of a comprehensive smoke management program. Table 15 provides a quick reference to specification

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(90) New York, State of. Part 215, 121 CN, 5-31-71, Open Fires, 1972. 3 pp.

TABLE 15. QUICK REFERENCE TO SPECIFICATION OPTIONS RELATED TO FUELS CHARACTERISTICS

Specification option	Technology for effecting option: Available	Relative level of sophistication	Emerging	Relative level of sophistication
Burn size (limits total emissions production)	Fire control methods for containing fire to an area with an acceptable amount of total available fuel	Simple	Typical case examples of downwind impacts for specific fuel types (9)	Simple
			Improved low-cost fuel inventory methods (91, 92)	Simple
			Table of available fuel at different fuel moisture levels for specific fuel types (9)	Moderate
Fuel loading (limits total emissions production)	Providing for shorter time intervals between burning of naturally occurring vegetation and litter	Simple		
	Encouraging better residues utilization	Moderate		
Pysical Arrangement (limits total emissions, promotes better convective lift)	Mechanical pretreatments (YUM, piling and windrows, chopping)	Moderate	Added and improved emission and heat release rates for different fuel treatments (25, 26)	Moderate
	Emission factors for different treatments (see Sec. 5, Figure 6)	Moderate		
	Supplemental specifications for limiting soil admixtures	Moderate		
Fuel Moisture (limits total emissions, promotes better convective lift)	"Fuel stick" analog	Simple	Tables of available fuel at different fuel moisture levels for specific fuel types (9)	Moderate
	Large fuels probes	Simple		
	Recommended fuel moisture ranges	Simple	Probable fuel moisture data for specified locations away from observation stations (93)	Simple
	Drying curves for fuels of different time lags	Simple		

options related to fuels characteristics (9, 25, 26, 91-93). Brief amplifying discussions follow the table.

Barring a natural disaster, such as wind or ice damage, fuel loading in naturally occurring vegetation and litter can be regulated by timing between burns. In the area of timber-harvesting residues, removal of the fuel through increased utilization will reduce the fuel loading.

Emissions per unit of fuel burned generally increase as fuel moisture content increases, so smoke management calls for burning at lower moisture contents. However, the drier the fuel, the greater the chances for a prescribed burn to become damaging and to escape. An example prescription recommendation is that prescribed burning be done 2 days to 3 days after 12 mm to 25 mm of rain have fallen, thus insuring that the soil will be moist and that the deep organic layers will not be burned. A preferred range for fine fuel moisture, affected readily by the relative humidity in the air, rainfall, and air temperature, is from 7 percent to 20 percent. For heavy fuel loadings, the moisture content should be kept near 20 percent to keep the fire from becoming hot enough to damage young growth, overstory crowns, and the soil (9).

Fuel arrangement can be influenced by various piling techniques that are normally applied to the burning of logging debris. Burning of piles also results in more rapid and complete combustion. It can be performed during a greater portion of the year because piles are less dependent on lower fuel moisture content (66).

Specification of Firing Technique

Firing technique options are limited by the type of fuel to be burned and the objectives of the prescription. Table 16 provides a quick reference to options related to firing technique. Brief amplifying discussions follow the table.

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(91) Maxwell, W. G., and F. R. Ward. Photo Series for Quantifying Forest Residues in the Coastal Douglas-Fir Hemlock Type. Forest Service General Technical Report PNW-51, U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, 1976.

(92) Schmidt, R. G. An Approach to Hazard Classification. Fire Management Notes, 39(4):9-11, 19, 1978.

(93) Paul, J. T. Forestry Weather Data Systems. Proposed Work Unit Description, Draft on file, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, 1979. 10 pp.

TABLE 16. QUICK REFERENCE TO SPECIFICATION OPTIONS RELATED TO FIRING TECHNIQUE

Specification option	Technology for effecting option			
	Available	Relative level of sophistication	Emerging	Relative level of sophistication
Backing fires (relatively less TSP emissions)	Both application guides and experienced personnel	Simple		
Timing of ignitions (avoidance of late afternoon and evening lessened atmospheric dispersion capacity & of downslope downcanyon night-time circulation)	Experienced personnel with knowledge of time for burnout	Simple	Decay-rate data for specific fuels and firing techniques (22)	Moderate
Use of forced-air methods (for collected debris only, reduces emission - limited application)	Air curtain devices	Moderate		

It has been shown quantitatively and qualitatively that firing technique affects emissions from forest fuels. Backing fires emit less total suspended particulate matter than heading fires apparently because backing fires have more glowing combustion, while heading fires have more flaming and smoldering combustion (9, 20, 94). Backfiring requires steady winds of 1.8 m/s to 4.5 m/s (5).

A relatively new technique called air curtain combustion is specifically designed for the combustion of wood waste with minimal smoke emissions. In this system, a blower directs an air curtain diagonally across the burning pile of wood thereby promoting rapid and complete combustion. Air quality evaluations show that the air curtain combustion process will produce no visible smoke emissions if combustion temperatures are maintained over 1,600°F (95). This technique is not widely utilized at present because of its high operating costs (66) and site disturbance.

Specification of Meteorological Scheduling

Prescribed fires can be set when meteorological conditions provide for the best dispersal of pollutants. "Best dispersal" is both directing plumes away from receptor areas where unwanted impacts are to be avoided, and obtaining maximum atmospheric diffusion. This broad area of technology is known as meteorological scheduling.

Meteorological scheduling options are many and may be combined. The Table 17 quick reference to these options is, thus, an

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(94) Yamate, G., J. Stockham, D. Becker, T. Waterman, P. Llewellen, and W. M. Vatavuk. Development of Emission Factors for Estimating Atmospheric Emissions from Forest Fires. Presented at the 68th Annual Meeting of the Air Pollution Control Association, Boston, Massachusetts, June 15-20, 1975. 15 pp.

(95) McLean, H. R., and F. R. Ward. Air Curtain Combustion Device Evaluated for Burning Heavy Fuels. R-6 Fuel Management Notes, 4(1):1-7, 1976.

TABLE 17. QUICK REFERENCE TO SPECIFICATION OPTIONS RELATED TO METEOROLOGICAL SCHEDULING

Specification option	Technology for effecting option			
	Available	Relative level of sophistication	Emerging	Relative level of sophistication
Forecast wind direction (avoids) critical receptor areas)	Local knowledge of areas to be avoided and used with National Weather Service fire weather forecast assistance[a]	Simple	ADP data for designated nonattainment areas - SMKLCR (73)	Moderate
			ADP weather observations and forecast localizing techniques for flat and rolling terrain (97)	Moderate
			Same as above for mountainous terrain (96)	Moderate
Forecast air pollution alert "stagnation index," mixing height and stability class limiters - include time of day (lessen risks of inversion-trapped smoke plumes)	National Weather Service fire weather forecasts[a] and smoke management training for "simple screening"	Moderate	ADP weather observations and localizing techniques for flat and rolling terrain (97)	Moderate
			Same as above for mountainous terrain (96)	Moderate
Single fire predicted downwind emission concentrations (avoids unacceptable concentration in downwind receptor areas)			ADP-determined single fire short-term peak concentrations predictions - PRESMOK (7, 30) and 24-hr. concentrations - HRSMOK (75)	Moderate
			ADP-determined single fire short-term peak and 24-hr. average concentration predictions using automatically interfaced nonattainment areas as well as observed and forecast weather variables - RXBURN (74)	Moderate
Multiple-fire management package for categories of burning days	Predetermined burning day categories (usig burning season climatology) and pre-allocated amounts of burning, with manual weather data comparisons by competent meteorologist(s)	High	Fully automated predetermined burning day categories (using burning season climatology) and pre-allocated amounts of burning. Utilizes accounting system with automatic interfacing of nonattainment area as well as 36-hr. and shorter term weather forecast and observed data to provide "burn/no-burn" advice (96)	Moderate
Multiple-fire management package for full examination of each day's prescribed burning capacity			Same as above, except makes more thorough use of individual fire prescriptions criteria to advise on best mixes of individual fires for maximized operation (96)	High

[a]Trends away from one-on-one meteorological assistance by the National Weather Service will further limit this availability.

abbreviation of the total technological capability possible (73-75, 96, 97). It will be noted that automated-data processing is shown with the more sophisticated levels of emerging smoke management technology in Table 17. This critical need to best use meteorological scheduling has been illustrated in Section 6 and is discussed again in Section 7.

Because prescribed fires are not bound to year-long, day-in-day-out operations, as with stationary sources, and because the better of atmospheric conditions can be used in scheduling their execution, questions are raised regarding the fit of prescribed fire to PSD provisions. These are related specifically to a need for prescribed fire increments, and to the appropriateness of using reduced prescribed burning as an offset for increments desired by proposed new sources (96).

Prime considerations in scheduling are mixing height, atmospheric stability, wind speed and wind direction. Atmospheric stability indicates the degree of thermally and mechanically induced turbulence in the atmosphere. Mixing height is that height to which ground-based thermal eddies extend. Smoke dispersal is best when the atmosphere is unstable and the mixing height is at great distance from the earth's surface. This is because the relative warmth of smoke plumes will cause them to continue to rise rapidly under these conditions until plume and atmospheric temperatures become equal; at that point, the smoke diffuses and is carried along in the air of which it has become a part. When high yields of heat are available, it is still possible to obtain satisfactory dispersal of the plume, so long as the temperature difference is present, even with less than these optimum atmospheric conditions. It must be stressed, however, that under extreme conditions of instability, the fire may burn out of control.

A special stability situation occurs when there is an inversion layer in which the air temperature increases with height. An inversion layer acts as a lid that tends to trap rising smoke

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(96) Pierovich, J. M. Current Activities and Future Plans for Smoke Management Research and Development at the Southern Forest Fire Laboratory. Manuscript at press, copy on file, U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, 1979. 6 pp. + appendices.

(97) Paul, J. T., and J. Clayton, et al. User Manual - Forestry Weather Interpretations System...(FWIS). U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Asheville, North Carolina, and Southeastern Area State and Private Forestry, Atlanta, Georgia, in cooperation with the U.S. Department of Commerce, NOAA, NWS. U.S. Government Printing Office, Washington, D.C., 1978. 83 pp.

columns near the earth's surface. As a consequence, prescribed burning is often precluded when an inversion layer is present (9, 66). On the other hand, inversions lower in elevation than the area where prescribed burning is being done tend to limit smoke below the inversion height. For example, slash burning in the Pacific Northwest frequently takes place in high, mountainous areas, so that meteorological scheduling is designed to keep pollutants from reaching population centers in the valleys. Under certain meteorological patterns, an inversion layer is desirable in helping to keep emissions above the valleys (8).

Wind direction during burning operations should be away from populated areas. For fires in the Southeastern United States, recommended optimum wind speeds are 2 mph to 10 mph near the ground and 5 mph to 18 mph at the 20-foot level (9). Within this range, the best wind speed depends upon the presence or absence of a tree canopy, upon the firing technique used, and upon the conditions of the fuel.

Meteorological scheduling is among the most viable of control technologies for operational smoke management plans. Among the tools of meteorological scheduling are EPA-recommended Gaussian dispersion models adapted for prescribed fires and for use of real-time weather data. This carries with it two elements of chance. One is in the statistical basis (i.e., uncertainty) of the Gaussian dispersion model. The other is in dependence upon rapidly disseminated, and as locally correct as possible, weather observations and forecasts. The probabalistic nature of model predictions, and of weather forecasts which they incorporate, is recognized by the land management community due to familiarity with these same elements in controlling wildfires and in other weather-affected operations. Rapid dissemination and localization of weather data do not represent a new concept, but the utility of these are being newly realized in a pilot test currently under way between the Forest Service and the National Weather Service (97). Burning permit systems in several states make this information vital to land managers, and smoke management modules in the referenced test are automatically interfacing localized near-real-time data with other inputs in decision aids that would not be usable otherwise.

SECTION 7

OUTLOOK

Prescribed fire is the major forest management method for reduction in intensity of wildfires and is also used to accomplish other management objectives such as silviculture, disease control, range improvement, and vegetation management, such as protection and/or enhancement of rare and endangered plant and animal species. At present, there is no satisfactory alternative to prescribed burning for many applications. Alternative approaches are generally more expensive, damaging to the environment, impractical, or unsuited for accomplishing needed land management objectives.

TRENDS

Some of the more important actions and trends that bear upon an outlook for prescribed fire are summarized in Table 18, along with some of the underlying reasons for these actions and trends. The projected net consequences to receptor areas from prescribed fire during the next decade are also presented, showing results of a subjective evaluation of the possible increases or decreases in emisions concentrations in areas of concern.

Although a meaningful projection of tons of produced emissions cannot be made from indicators in Table 18, the net effect in receptor areas is predictable. To make such a prediction, we must first examine the actions and trends that will decrease concentrations in receptor areas of concern. From these, it will be seen that prescribed burners are expected to continue to adopt available and emerging smoke management technology. Actions have been taken to improve upon utilization of residues that would be left behind in timber-harvesting operations. Work to encourange energy production from biomass cleared for silvicultural reasons is an example of how this trend may be continued. Smoke management, though also encompassing alternates to burning, bears most heavily upon reduced emission concentrations in receptor areas. By taking advantage of the best-available control technology, the land manager-burner may predict downwind concentrations, may better direct smoke plumes away from areas of concern, and may limit the amounts of fuel burned on any one day as necessary. He may also apply burning and pretreatment measures that will promote more complete combustion with attendant lessening of emissions.

TABLE 18. SUMMARY OF SOME OF THE MORE IMPORTANT ACTIONS AND TRENDS, THE UNDERLYING REASONS, AND PROJECTED NET CONSEQUENCE TO RECEPTOR AREA EMISSIONS CONCENTRATIONS

Actions and Trends	Underlying reasons			Projected net consequence to receptor areas concentrations in next 10 years			
				Increases		Decreases	
	Economic	Energy Sources supply & demand	Responses to Clean Air Act	Strong	Lesser	Strong	Lesser
Presidential decision to accelerate cutting of Federal timber	✓				•		
Further changes from alternate methods to use of prescribed fire	✓	✓		•			
Further changes to alternate methods from use of prescribed fire							
Increased utilization	✓	✓	✓			-	
Other		No significance					
Need to reduce expenditures for wildfire presuppression and suppression	✓	✓		•			
Public safety			✓				
PSD visibility regulations			a	a		a	
Loss of alternative treatment methods-herbicides	✓			•			
State Implementation Planning			✓			-	
Transfer and adoption of smoke management technology			✓			-	
Completion of conversions from old-growth (virgin) to second growth forests	✓					b	
Reintroduction of fire wildland ecosystems[c]	✓				•		

[a] If pending PSD visibility regulations are applied to prescribed burning there will be a strong decrease of impacts from prescribed fire emissions in this decade, but this is believed to be a precursor to a strong upward trend in wildfire emissions in the last half of this decade and in subsequent decades.

[b] Effect will not be felt in this decade, but will be substantial within 3 to 5 decades.

[c] Also, to manage ecosystems in natural state in selected areas, i.e., Wilderness and National Parks.

Next, examining the actions and trends that will tend to increase emissions, it can be seen from Table 18 that most will exert a strong increase tendency. While the national timber supply is roughly two-thirds from other lands, the recent Presidential direction to increase timber supplies from federal lands will have an effect of increasing emissions. This direction, reflecting a determination to improve efficiency and management of the Nation's federal timber reserves through a temporary departure from a non-declining, even-flow policy, will be felt most in the defective oldgrowth (i.e., virgin) stands of the West where more residues will require treatment (98). Economic pressures are expected to call for placing more land in full production of commercial forests by preparing sites now occupied by brush and commercially undesirable species. But, as costs climb and as energy sources and herbicides are less available, it is inevitable that some alternative treatment methods will be foregone in favor of more use of prescribed fire. Except in the area of increased utilization, as discussed already, any shift from prescribed fire to alternate methods will be of no significance to decreases in concentrations of emissions in receptor areas. Economic and energy-related reasons also underlie changes in wildfire presuppression and suppression policies (99); among alternatives under examination will be added installation of "fuel-free" corridors, fuel breaks, uneven-aged vegetation mosaics created by the use of fire, and general reduction of fuels which have accumulated under past fire exclusion policies. While these changes in policy will have a strong emissions increase tendency, a related policy change toward reintroduction of fire to wildland ecosystems (especially in wilderness and in National Parks) will be of generally lesser importance. Overall, the emissions increasing actions and trends are expected to be of most importance in the Western States. From this examination of the emissions decreasing and increasing trends and actions, it is predictable that while more emissions will be produced, the overall net consequence to concentrations of emissions in areas of concern will be less during the next decade than at present.

APPLYING THE TECHNOLOGY

Questions that have tended to impede implementation of control technology are daylighted in Section 6 of this report. A paramount question among these has been lack of guidance, or of

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(98) Carter, President James. Memorandum for the Secretary of Agriculture, The White House, Washington, D.C., June 13, 1979. 1 p.

(99) Gale, R. D. Evaluation of Fire Management Activities of the National Forests. Policy Analysis Staff Report, U.S. Department of Agriculture, Forest Service, Washington, D.C., 1977. 127 pp.

commitment, on the part of air quality regulatory agencies for acceptance of those measures which might be implemented. It is anticipated that during the next decade land managers and air quality personnel at all levels will enhance air quality by an increased sharing in this evolutionary process, in order that the best-available control technology can be effected to appropriate levels.

The intermittent or temporary nature of prescribed fire has resulted in mixed interpretations among land managers and air quality personnel at the State level. Some believe that because it is a temporary source, prescribed fire does not come under the Clean Air Act PSD provisions at all. This is a question of special importance where there is strong competition for PSD increments or where prescribed burning activity is expected to increase.

One balancing factor recently advanced (100) is based on the EPA Offset Policy, whereby an increase in pollution from a new source can be offset by a reduction in emissions from other existing sources. The rationale of this concept is that prescribed fires will offset emissions from wildfires that would otherwise take place and produce substantially higher emission levels.

The outlook for evolution of applications of control technology will depend in many areas upon availability of data processing systems which make near-real-time weather data, and automated processing of interfaced weather data, prescribed fire data, and operational dispersion modeling a reality. Even in areas where simple screening procedures and checklists will serve prescribed burners without further sophistication, the importance of reliable local weather information cannot be minimized. Continuation of the Forest Service and National Weather Service cooperative pilot test referenced in Section 6 will be dependent upon conversion to an operating system in the future, but this possibility cannot be definitely assessed at this time.

CONCLUSIONS

A nonspeculative conclusion possible through the preceding discussions is that prescribed fire emissions will increase, but that the net impact of this increase in production will not be crucial, due largely to voluntary actions taken among land managers. Somewhat more speculatively, it is possible to conclude

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(100) Pierovich, J. M. Resource Management-Smoke Management: Some Common Operational Priorities. Informal paper presented at the Fall Section Meeting of the Society of American Foresters, Ocala, Florida, October 10-11, 1978.

that land management and air quality personnel will have common points of communication concerning an available and emerging technology, and that this communication will result in a desirable evolution of both voluntary and regulated processes. The net result should be a strong downward trend in concentrations of emissions in receptor areas.

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GLOSSARY

air quality: Atmospheric properties with respect to the presence of pollutants which may impair health, visibility or general welfare.

area ignition: Fires set in many places throughout an area either simultaneously or in quick succession and spaced so that the entire area is rapidly covered with fire.

available fuel load: The fuel load that will be consumed in a fire under given conditions.

backing fire: A prescribed fire or wildfire burning into or against the wind or down the slope without the aid of wind.

brush: Scrub vegetation and immature stands of tree species that do not produce merchantable timber.

burying: A residue disposal treatment in which residue is collected, placed in a large pit or trench, and covered with soil; usually done with a tractor.

chapparal: A plant community comprised of stiff or thorny shrubs widely distributed in Southern California.

chipping: (1) In residue treatment, the reduction of woody residue by a portable chipper to chips that are left to decay on the forest floor. (2) In utilization, the conversion of usable wood to chips, often at the logging site, for use in manufacture of pulp, hardboard, energy, etc.

clearcutting: A harvest and regeneration system, normally applied to an even-aged forest, whereby all trees are cut. Regeneration may be artificial or natural, logging methods may vary, and clearcut areas may be of any size.

convection: The transmission of heat by the mass movement of heated particles, as circulation in air, gas, or liquid currents. In meteorology, convection refers to the thermally induced, vertical motion of air.

convective plume height: The elevation a plume attains due to buoyancy caused by its initial increased temperature over ambient conditions.

convective smoke column: The thermally produced ascending column of hot gases and smoke over a fire.

call logs: Inferior or diseased logs removed from a forest, or logs removed for thinning.

duff: Forest litter and other organic debris in various stages of decomposition, on top of the mineral soil, typical of coniferous forests in cool climates where rate of decomposition is low and litter accumulation exceeds decay.

emission factors: Statistical average of the amount of emissions released to the atmosphere in relation to the amount of fuel burned. It is generally expressed in g/kg.

criteria pollutants: Air pollutants for which national ambient air quality standards have been set.

fine fuels: The complex of living and dead herbaceous plants and dead woody plant materials less than 6 mm in diameter.

fuel loading: The amount of fuel present expressed quantitatively in terms of weight of fuel per unit area. This may be available fuel or total fuel and is usually dry weight.

fuel moisture content: The quantity of water in a fuel particle expressed as a percent of the oven dry weight of the fuel particle.

Gaussian plume: A plume in which the concentration of the pollutant material is distributed according to the normal distribution (the fundamental frequency distribution of statistical analysis) in the crosswind and vertical directions.

heading fire: A fire spreading or set to spread with the wind and/or upslope.

herbicide: A chemical compound that causes physiological plant damage usually resulting in death.

humus: That more or less stable fraction of the soil organic matter remaining after the major portion of plant and animal residues have decomposed; usually dark colored.

landing: Anyplace on or adjacent to the logging site where logs are assembled for further transport.

litter: The surface layer of the forest floor consisting of freshly fallen leaves, needles, twigs, stems, bark, and fruits. This layer may be very thin or absent during the growing season.

logging residue: Unmerchantable or otherwise unwanted woody material remaining after a logging operation.

non-attainment area: Region of the country where national ambient air quality standards are not being met.

old growth: Timber stands of age and stature so as to resemble a virgin forest in which the mean annual growth is declining.

plume: A cloud of pollutant material, containing emissions from a particular source or group of sources, which is being dispersed in the atmosphere.

prescribed burning: The skillful application of fire in forest and range management under conditions of weather, fuel moisture, and soil moisture that will confine the fire to a predetermined area resulting in planned benefits such as fire hazard reduction, control of understory species, seedbed and site preparation, grazing enhancement, wildlife habitat improvement, and forest tree disease control.

pyrolysis: A heat-induced, endothermic chemical degradation.

ring fire: Fires started by simultaneous ignition around the perimeter of an intended burn area, which burns toward the center.

scarification: Clearing away all vegetation to expose the soil.

second growth: Natural or planted timber stands on areas previously logged or cleared.

silviculture: A phase of forestry dealing with the care of forest trees.

site preparation: Removal or killing of unwanted vegetation, residue, etc., by use of fire, herbicides, or mechanical treatments in preparation for reforestation and future management.

slash: A complex of woody forest debris left on the ground after logging, land clearing, thinning, pruning, brush removal, or natural processes such as ice or snow breakage, wind and fire. Slash includes logs, chunks, bark, branches, tops, uprooted stumps and trees, intermixed understory vegetation, and other fuels.

smoke management: Providing quantitative appraisals of prescribed fire and specifying conditions that limit air quality impacts in areas of concern.

smoldering combustion: Combustion of a solid fuel, generally with incandescence and smoke but without flame.

succession: The sequence of identifiable ecological stages in the biological population of an area.

yarding: Moving of logs from stump to roadside deck or landing.

YUM: Yarding unmerchantable material by cable techniques, usually in areas inaccessible to tractors.

CONVERSION FACTORS AND METRIC PREFIXES (101)

CONVERSION FACTORS

To convert from	To	Multiply by
Degree Celsius (°C)	Degree Fahrenheit (°F)	$t_{°F} = 1.8\ t_{°C} + 32$
Gram/kilogram (g/kg)	Pound/ton	2.000
Joule (J)	Btu	9.478×10^{-4}
Kilogram (kg)	Pound-mass (avoirdupois)	2.205
Kilometer (km)	Mile	6.214×10^{-1}
Meter (m)	Foot	3.281
Meter (m)	Inch	3.937×10^{1}
Meter^2 (m^2)	Mile^2	3.861×10^{-7}
Metric ton	Ton (short, 2,000 pound mass)	1.102

PREFIXES

Prefix	Symbol	Multiplication factor	Example
Tera	T	10^{12}	1 Tg = 1 x 10^{12} grams
Giga	G	10^{9}	1 Gg = 1 x 10^{9} grams
Mega	M	10^{6}	1 Mg = 1 x 10^{6} grams
Kilo	k	10^{3}	1 km = 1 x 10^{3} meters
Milli	m	10^{-3}	1 mm = 1 x 10^{-3} meters
Micro	μ	10^{-6}	1 μm = 1 x 10^{-6} meters

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